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ANALYSIS OF SHIP DEPLOYED LINE ARRAY DYNAMICS

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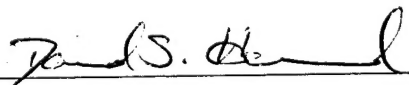**Office of Naval Research (Code 321)**
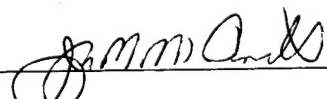**Arlington, VA 22217-5000**

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13. ABSTRACT (Maximum 200 words)

Airborne Rapidly Deployable Technology (ARDT) is being investigated by the US Navy. One of the areas crucial for the project's success is an in-water deployment of an array. In a recent trial, instrumented arrays were deployed from a moving ship and allowed to descend to the bottom. The purpose of this trial was to demonstrate an ability to deploy a long array of sensors in this manner such that the array has a stable descent and regular element spacing on the bottom. An analysis of the results obtained from that trial is presented. Two arrays were successfully deployed. The depth histories of various points along the array and the location of the array on the bottom were obtained for each deployment. The results indicated that the arrays achieved stable descent rates and were placed on the bottom with regular element spacing. The SEADYN cable dynamics model was used both to design the arrays before the trial and to attempt to replicate the trial results. It was successful in both tasks. The experiment and subsequent analysis indicated that arrays can be designed to descend through the water column to the bottom in a stable and predictable manner after being deployed from a moving platform.

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SUMMARY

Introduction

This experiment was conducted in response to concerns expressed by The Technical Cooperative Program Subgroup G Technical Panel 9 (TTCP GTP-9) as to the deployment of rapidly deployable systems in shallow water and the capability to reliably model the dynamics of these systems. Proposed concepts such as the US Airborne Rapidly Deployable Sonobuoy (ARDT) require a long horizontal array to be deployed from the air, land on the ocean surface and descend to the bottom in an orderly fashion. This is an area of high technical risk and accurate modeling of this scenario is required. The TTCP nations met and a common computer model, SEADYN, was selected to perform deployment dynamics simulations. It was then decided that a trial should be conducted in order to validate SEADYN's effectiveness and demonstrate off ship deployment capabilities. A joint trial was planned to deploy a split horizontal array of sensors from a moving research vessel. The array would be populated by sensors such that the motions of the array could be tracked during descent and the on the bottom positions could be located.

Summary of Results

Two instrumented split line array systems (each system consisting of two sub arrays and an inter-array line connecting them) were successfully deployed from a moving vessel by utilizing a multiple bobbin payout arrangement. The arrays were allowed to descend to the bottom. The descent dynamics were characterized by depth loggers spaced along the arrays. Transponders positioned at the array ends located the arrays on the bottom. Steady descent rates and regular element spacings were achieved for three of the four sub arrays that went into the water.

SEADYN simulations were run using available environmental data collected during the trial. The model was able to predict the descent dynamics of the deployments conducted. Favorable comparisons were made between the experimental data and the simulation results in terms of bottom arrival times, element spacings on the bottom, and nodal depth histories. The simulation comparisons were well within experimental error.

Conclusions

The primary objective of the trial was to demonstrate that an instrumented array could be deployed from the surface and arrive on the bottom in a straight line and with known element spacings. Transponders located at the ends of each of the two arrays in the split line arrangement verified that this was accomplished if the deployment vessel held a steady course. Deployment 1 array spacings were calculated to be greater than the 150 foot original spacing. A combination of transponder accuracy, and the exact amount of cable wrapped on each bobbin accounted for the increased lengths; however, it is unlikely that the elements were bunched or tangled, and it is likely that the elements were spaced at roughly equal intervals. The same argument could be made about the second array in deployment 3. The 141 foot average spacing calculated for the first array in deployment 3 indicated less confidence that all the elements had regular spacings. This is probably due to the track taken by the payout vessel as this array was being extracted.

Another objective of the trial was to establish the ability to deploy the split line array from a moving vessel at sea. The use of multiple small bobbins to extract individual array elements proved to be a viable technique. Although two successful deployments were conducted out of the three attempted, 80 of the 81 array bobbins that had the chance to deploy were paid out without incident, and all nine inter-array bobbins were used successfully. In addition, the problem with the second deployment was believed to be a setup problem with the transponder attachment service loop. Until the payout procedure reached the transponder, the first array, as well as the inter-array cable deployed perfectly.

The descent dynamics of the system were successfully characterized by the use of depth logging sensors. The data from these units was compared to computer simulation results for validation purposes. Successful validation allowed the computer model to be used with increased confidence in the design phase.

The SEADYN model performed very well in simulating the dynamics of the system after the trial was conducted. The simulations indicated that the array sections had stable descent characteristics, and that the relatively heavy transponders located at the array ends compromised element spacings. High values of cable drag coefficients that were needed to model the deployments implied that the cables were strumming during descent. Model results also revealed that the parachutes were not operating at maximum effectiveness and one parachute appeared not to have inflated at all.

However, the model was limited by the quality of the environmental data collected on site and the extent of knowledge about the payout dynamics. In addition, for the model to be used with confidence as a design tool for future systems, accurate predictions must be made before trials are run. This would require knowledge of the cable coefficient of drag when the cable is undergoing vortex shedding, potential environmental conditions and payout dynamics, and, in this case, the effects of partial parachute deployments. These parameters would have to be taken into account by conducting multiple simulations, each one varying the relevant parameters in an attempt to bracket worst case scenarios and predict nominal performance.

Recommendations

The problem of drag amplification in cables experiencing oscillations due to vortex shedding (strumming) is well known and much studied. However, a feasible model has not been developed for long flexible cables with highly variable geometry and relative velocities and with attached masses. The drag forces on a cable could be amplified by a factor of greater than two in some cases, and this could have detrimental effects to a system dominated by cable drag. An effort should be made to model this effect and validate the results.

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DISCUSSION

Background

The Airborne Rapidly Deployable Technology project seeks to develop techniques to deploy large arrays of acoustic sensors on the sea floor from a remote platform. This is to be accomplished, in one of its configurations, by launching an autonomous glider from a P-3 aircraft, which will fly to the area of interest and pay out an array in the air along a predetermined course. The array must descend through the water column and lie on the bottom fully extended. For maximum utility, this scenario must take place regardless of array orientation, ocean current conditions, or sea state; therefore, a reliable, robust technique must be developed to situate the array of sensors on the bottom.

From the onset of the development program, the in-water descent of an ARDT array was considered to be an area of concern and an effort was undertaken to determine how best to accomplish this portion of the deployment. Computer modeling was used as a design tool to evaluate various deployment schemes, and candidate techniques were investigated through scale model experimentation.

A computer model was developed at the Naval Air Warfare Center Aircraft Division Warminster to simulate the dynamics of a horizontal line array descent. The model, called FELL for Falling Extended Linear Line, was used to predict the deployment dynamics of various array designs without the expense of experimental testing.[1] FELL was intended to give a simple first order look at the cable dynamics posed by the ARDT deployment. Simulations using existing cable models were found either to fail to give satisfactory results or to require run times that were unacceptable (greater than 48 hours). At this initial stage of development, it was felt that precise accuracy should be sacrificed for faster run times because a high number of design iterations were required to bracket array design parameters.

A parametric study was conducted using the FELL model to ascertain the most important parameters needed to design an array to have a stable descent. The array configuration studied was one consisting of a line array of elements connected by lengths of cable to generic end bodies. It was found that the ratio of end body weight to array weight and the ratio of end body drag to array drag were good predictors of deployment stability[2]. A stable region for desired array designs based on these two ratios was identified.

In August of 1993, an experiment was conducted off of Key West in an attempt to validate the FELL computer model[3]. Instrumented arrays, designed according to FELL simulation results, were stretched over the ocean surface, released and allowed to descend to the bottom. Array elements sensed pressure and logged depth at one second intervals as the array descended, and a remotely operated vehicle (ROV) was used to locate the elements on the bottom, both through visual inspection and acoustically by emitting pings over the element location. The depth logger units provided a good check against FELL descent rate predictions; however, due to severe environmental conditions, acoustic fixes via the ROV failed to map accurate on the bottom locations of the array elements.

As part of TTCP GTP-9 Rapidly Deployable Systems (RDS) effort, the generic cable model SEADYN[4,5] was suggested as an alternative to the numerous application specific cable models, including FELL. SEADYN was capable of simulating ARDT-type

deployment situations, although run times on the order of 48 hours were often required. This longer solution interval was now considered acceptable because the design parameters established with the FELL model and the parametric study had provided some general guidelines for array design, resulting in fewer required design iterations. In addition, SEADYN had a long history of validation[6,7,8] and provided the capability to simulate an ARDT system from glider payout to ocean bottom without significant modification. For these reasons the further use of FELL was abandoned and SEADYN became the primary design tool for the development of ARDT systems.

Building on the results of the Key West deployments and subsequent computer modeling, a deployment test was conducted at the Naval Undersea Warfare Center Seneca Lake facility in October of 1994[9]. Seneca Lake provided a more controllable testing environment. In this test, a line array of depth logging sensors was stretched out over the surface from a barge, released and allowed to descend to the bottom. Four pingers evenly spaced along the array in conjunction with a field of moored sonobuoys gave an indication of the location of the array on the bottom. At one end of the array was a cylindrical weight, while at the other end of the array end bodies were alternated between a parafoil, a parachute and another cylindrical weight. Six deployments were successfully completed. SEADYN simulations run after the test produced results that closely matched the descent velocities and bottom arrival times of the depth sensors. The bottom location positions, however, were difficult to reproduce because of the lack of current profile data. In addition, the tension in the array line prior to deployment as a result of stretching the array across the surface caused the array ends to spring toward the center of the array. This motion made proper deployment of the parafoil difficult. It became clear that a better deployment method, and better environmental characterization were needed to fully describe the deployment dynamics.

The trial described in this report was an effort to solve the problems experienced in previous trials and to try to more closely replicate an ARDT deployment situation and array configuration. The purpose of this trial was to demonstrate an ability to deploy long arrays of sensors from a moving ship, to characterize the in water deployment dynamics of an ARDT type split horizontal line array, and to validate the results with the SEADYN computer model.

Array Design

The final array design is shown in Fig. 1, and Table I lists the physical characteristics of the array. The array was based on the ARDT conceptual design: two arrays of hydrophones connected by an inter-array cable. It was designed to function on the ocean floor. The array elements for this trial were a combination of autonomous depth loggers (ADL's), transponders and dummy elements. Five ADL's populated each sub array with transponders co-located at the ends. Dummy elements, designed to have the same wet weight and size as the ADL's but without depth measurement capability, were spaced between the ADL units such that each sub array had 17 units, either dummy or ADL, at sixteen 150 foot intervals making each sub array 2400 feet. The array line was 1/8 inch jacketed kevlar line and the inter-array cable was 1/16 inch diameter line of the same construction. The diameter and wet weight of these lines were selected to be approximations of ARDT candidate fiber optic cables. The inter-array cable was designed

to be 3750 feet or 25 element spacings. Two ADL units were placed symmetrically along the inter-array cable. At either end of the system were parachutes connected to the end of both sub arrays by a portion of array cable two element spacings long. The parachutes were used to control the descent. It was expected that the inter-array cable would act in a similar fashion to the parachutes, providing drag at the innermost ends of the arrays (positions 5 and 8 in Fig. 1). The two sub arrays would move towards each other during descent, but they would arrive on the bottom at the same time and element spacings would remain constant.
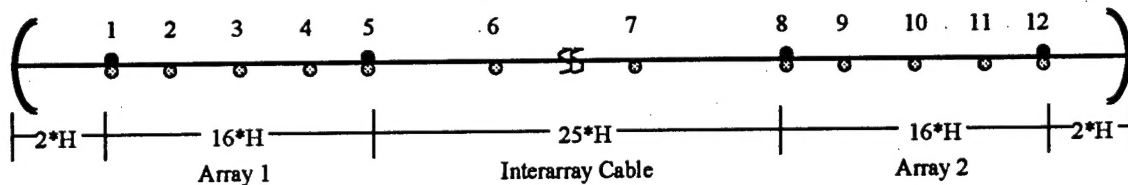
H = 150 ft
Overall Length = 9150 ft

- Transponder] Transponder and depth logger weight and drag designed to
- Depth Logger] match actual hydrophone configuration

(Parachute - Drag area determined by drag and weight of system

Figure 1 - Array design schematic

The autonomous depth loggers recorded depth at two second intervals. The recorded data were downloaded from the unit after the array was recovered. The ADL's consisted of a millivolt pressure sensor, electronics to record the pressure sensor output, and a nine volt battery, all housed in a watertight resealable PVC container. The size and weight of the units was on the order of magnitude of the ARDT proposed hydrophones. Five ADL's populated each array in a symmetric fashion as shown in Fig. 1.

The transponders, located at the ends of the arrays (Fig. 1), were used to provide on the bottom locations of the array ends. This was accomplished by interrogating the transponders with a towed projector to which the transponders responded at different frequencies. After several passes with the projector an accurate position could be obtained. The transponders were heavy compared to the ADL's (and the ARDT intended hydrophones). Because of this, buoyant material was added to the units to decrease the wet weight.

The parachutes were sized to balance the drag provided by the inter-array cable, so that each sub array had equal drag forces at either end. Computer simulations were run in various current environments using a range of cable drag coefficients, C_d's, and it was determined that some ballasting would be required at the parachute ends for a steady descent.
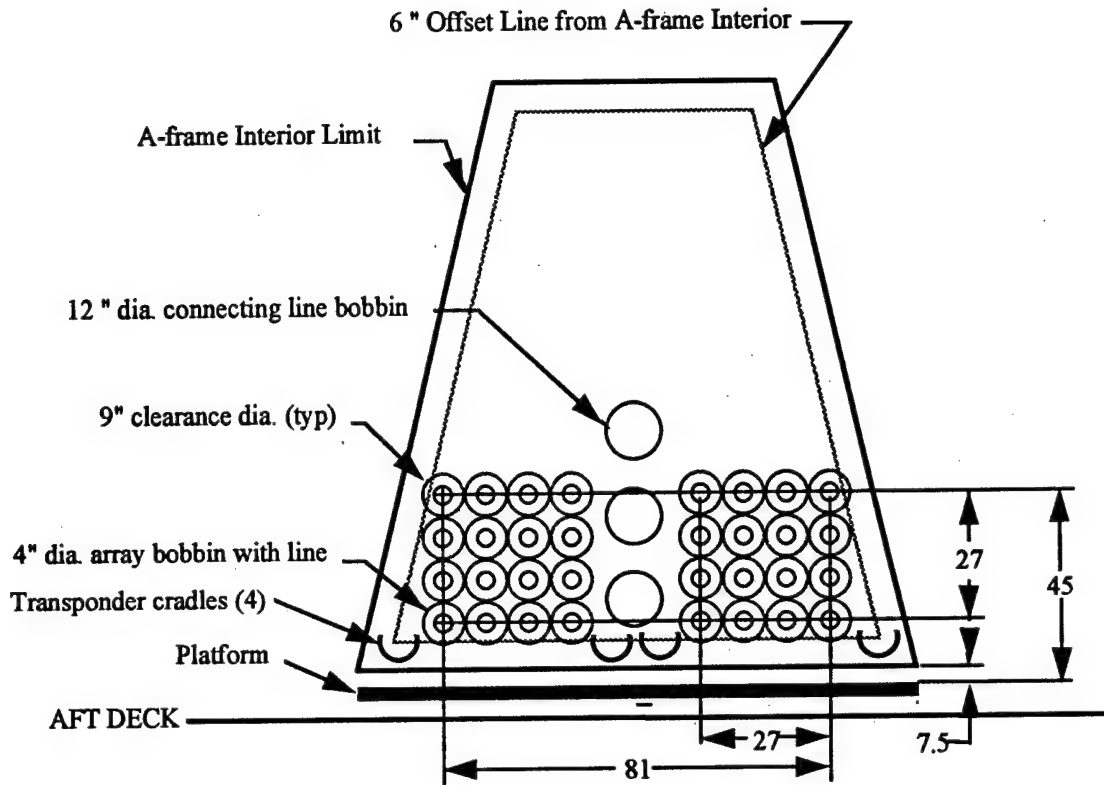
Component Dimensions	Value	Unit
Total Array Length	2400	ft
Total Inter-array Length	3750	ft
Array Cable Wet Weight	.00166	lb/ft
Array Cable Diameter	.132	in
Inter-array Cable Wet Weight	.00083	lb/ft
Inter-array Cable Diameter	.062	in
ADL Wet Weight	2.72	oz
ADL Diameter	2.25	in
ADL Length	6	in
Transponder Wet Weight	.5	lb
Transponder Diameter	6	in
Transponder Length	14	in
Dummy Unit Wet Weight	3.52	oz
Dummy Unit Diameter	2.25	in
Dummy Unit Length	6	in
Parachute Ballast Wet Weight	1.3	lb
Parachute Drag Area	31.87	sq ft

Table I - Array physical characteristics

Deployment Technique

Deployment of the system from a moving ship was achieved by using a multiple bobbin arrangement situated on the edge of the aft deck of the research vessel, CFAV Quest. Fig. 2 shows a schematic of the bobbin arrangement. Two sets of sixteen smaller array bobbins were arranged in a 4 by 4 square, while between the two sets of array bobbins were three larger inter-array bobbins arranged vertically. The transponders lay in four semicircular cradles positioned beneath and to either side of the array frames. The bobbins were attached to a frame that was secured to a platform under an A-frame. The bobbin frame pivoted to allow the entire set of bobbins to be tilted back 90 degrees for ease of pre-deployment preparation and inspection.

The array bobbins (Fig. 3) were constructed out of 4 inch diameter PVC pipe. They were 14 inches long with a slot running 12 inches from one end. Two layers of array cable were wound around the bobbin along 11.5 inches of the bobbin length such that 150 feet of the array line would fit. The bobbins were wound alternately in a clockwise and counter-clockwise direction to provide a torque free payout. An array element, either an ADL or a dummy, was attached to the inner wall of the bobbin with Velcro. The array cable was pulled off the bobbin starting at the front edge outer layer continuing towards the rear and to the bottom layer and back towards the front of the bobbin. The array element was attached to the array line at this point and it was pulled from the bobbin. The array line continued to the next bobbin by passing through the empty slot which was no longer covered by the wrapped array cable.

6 " Offset Line from A-frame Interior

A-frame Interior Limit

12 " dia. connecting line bobbin

9" clearance dia. (typ)

4" dia. array bobbin with line

Transponder cradles (4)

Platform

AFT DECK

27

45

27

81

7.5

All dimensions in inches

Figure 2 - Deployment bobbins arrangement on aft deck

The inter-array bobbins were larger, roughly 12 inches diameter by 24 inches long and were able to accommodate 1250 feet of the smaller inter-array line. The payout of the inter-array section occurred in a similar fashion to the array payout: starting with the outer layer at the front edge, back to the rear, and continuing to the inner layer back up to the front edge at which point an ADL was extracted. The ADL was not attached to the inner surface of the bobbin, but was mounted on the front surface of the bobbin in a foam cradle. The line passed through the slot and continued to the next bobbin.

The transponders were held in place with Velcro in the transponder cradles. They were extracted from the cradles by the array line at either end of the arrays. Because of the relatively large mass of the transponders, a length of bungee was put in line between the extracting line and the unit. ADL's were co-located with the transponders.

The deployment was initiated by lowering the first parachute to a waiting zodiac. Once the zodiac crew and deck crew were ready, the research vessel accelerated to its top speed away from the stationary zodiac. The cable connecting the parachute to the array was spooled off a bobbin similar to the array bobbins then attached to the first transponder and on to the rest of the array. After the last transponder was extracted, the line connecting the second array to the last parachute was spooled off and a parachute was pulled into the water. This parachute was packed in a plastic bag that was connected to the research vessel by a length of line. The parachute was extracted from the bag after it

was in the water and away from the propeller turbulence. At the same time the final parachute went off board, on radio command, the zodiac crew released the first parachute.

Array bobbin   Wrapped array cable

From previous bobbin first end paid out

Top layer payout direction

Bottom layer payout direction

To next bobbin

Last wrap, to ADL

Representative bottom layers

ADL / Dummy unit
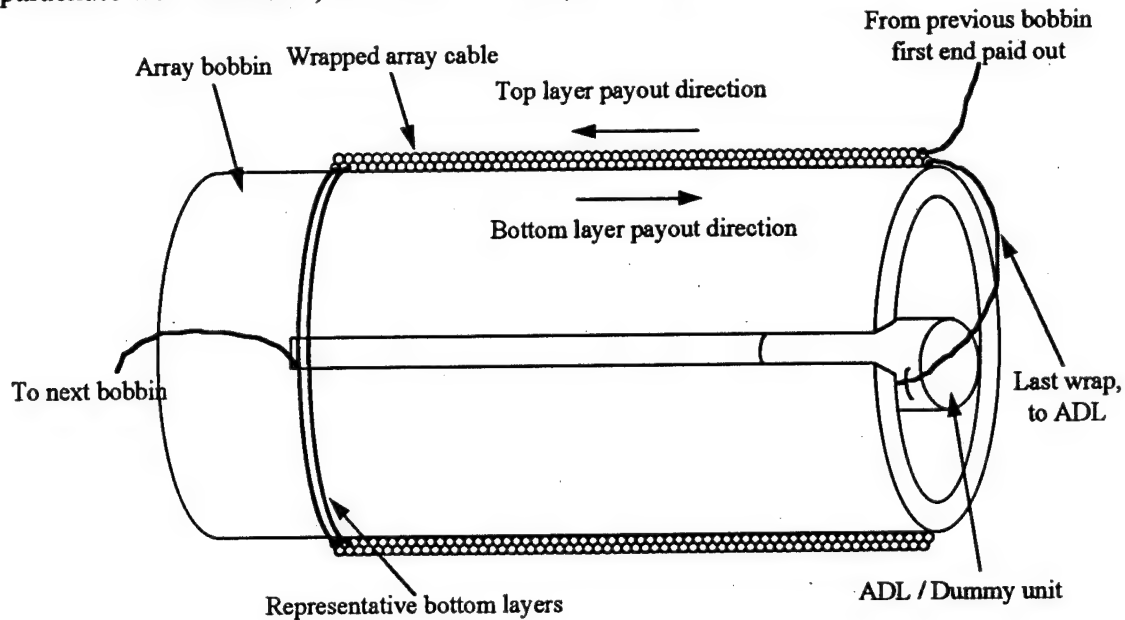
Figure 3 - Array bobbin isometric view

Recovery

Two methods were employed to ensure recovery of the deployed equipment (Fig. 4). At the zodiac end, a moored line was attached to the array. This line descended with the array when the parachute was released. Because the line was slightly negatively buoyant, and it was very long, there was minimal impact on the descent dynamics of that end. Recovery was achieved by snagging the mooring float and pulling up the recovery line and subsequently the array end.

RV Quest

Zodiac

Recovery line

"U" Gate

Decending array

Figure 4 - Recovery methods

The second method involved the use of a "U" shaped gate. A gate was set up by mooring two floats about 1000 feet apart and connecting the anchors with heavy line lying on the bottom. The gate was situated such that the array would be deployed through the gate. If recovery failed at the zodiac end, both of the gate floats would be snagged and the gate pulled to the surface along with the array line lying on top of the line connecting the anchors.

Experimental Results

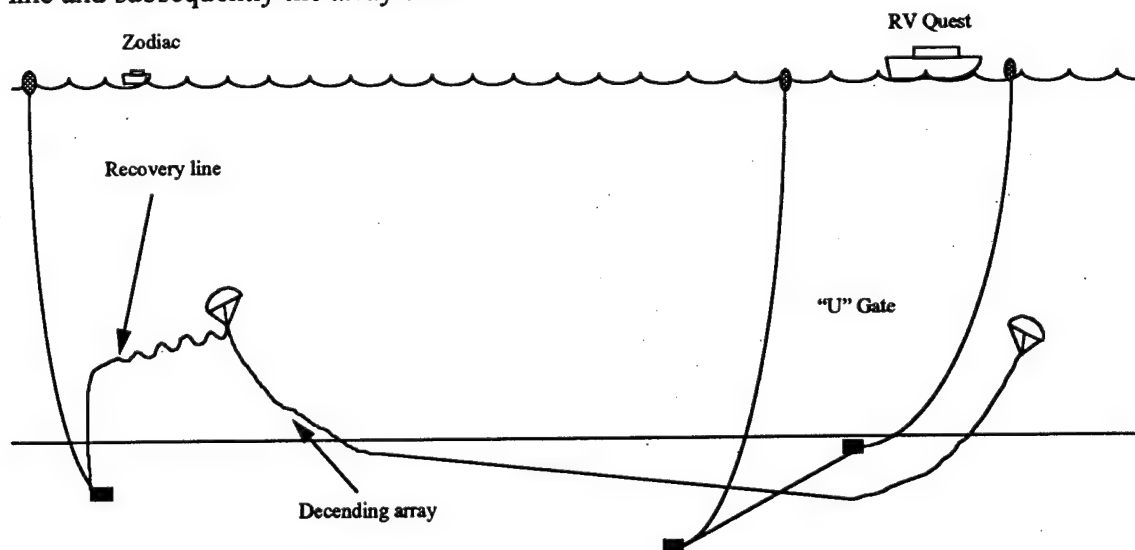Three deployment evolution's were attempted, and a fourth was prepared during the course of the trial. The system was successfully deployed off the ship and into the water during the first and third deployment evolutions. A snag occurred halfway through the payout of the system during the second deployment and a fourth deployment was canceled due to poor weather.

Deployment 1 - 26 October 1995

The day of the first deployment was sunny and warm, with light winds and a calm sea. Prior to deployment, current profile data were collected at four sites in the proposed area of operations using an acoustic doppler current profiler (ADCP). Current velocities in the north and east directions at several depths were taken at time intervals. After the bad data points were discarded, the remaining data were averaged at each site. The resulting profiles from two of the sites were very consistent and the data from both sites were averaged. A fifth degree polynomial curve fit was then applied. The averaged data and the curve fitted data are shown in Fig. 5, where negative north values indicate a southward current and negative east values represent a westward current. The smooth lines without markers are the fitted curves for the respective averaged current profiles as indicated on the chart. On the day deployment 1 was conducted there was a prevailing eastward current that decreased with depth and a southerly current that started at zero, peaked at around 400 feet and fell again to zero at the bottom.
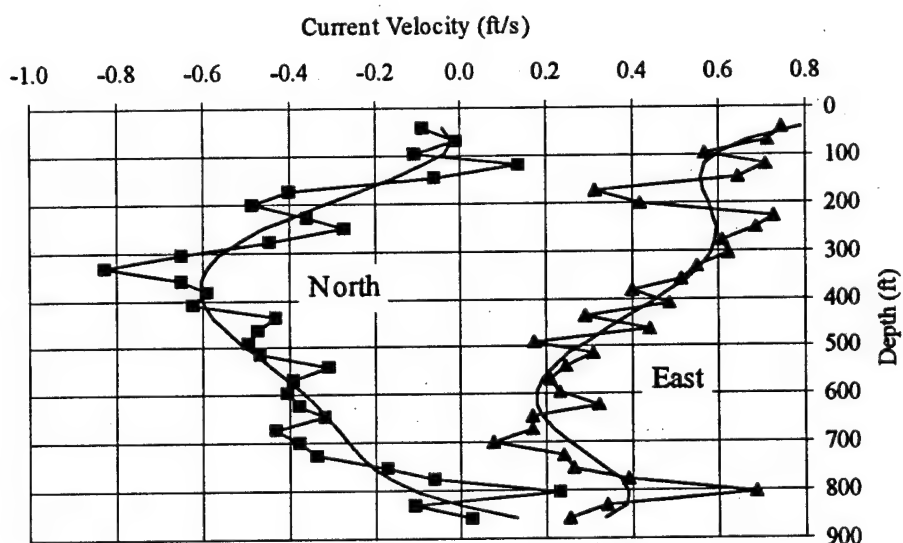

Figure 5 - Deployment 1 current velocity profiles

During the actual deployment operation the ship's non-acoustic data acquisition system (NADAS) recorded navigational and environmental data at 15 second intervals. Of particular relevance to this trial were the global positioning satellite (GPS) data, the ship's speed and heading over ground, and depth soundings along the deployment track. The NADAS GPS readings, and speed and course over ground data are shown in Figs. 6 and 7 respectively. The depth readings along the deployment track indicated a fairly flat bottom averaging 890 feet with one apparent valley that reached roughly 940 feet.
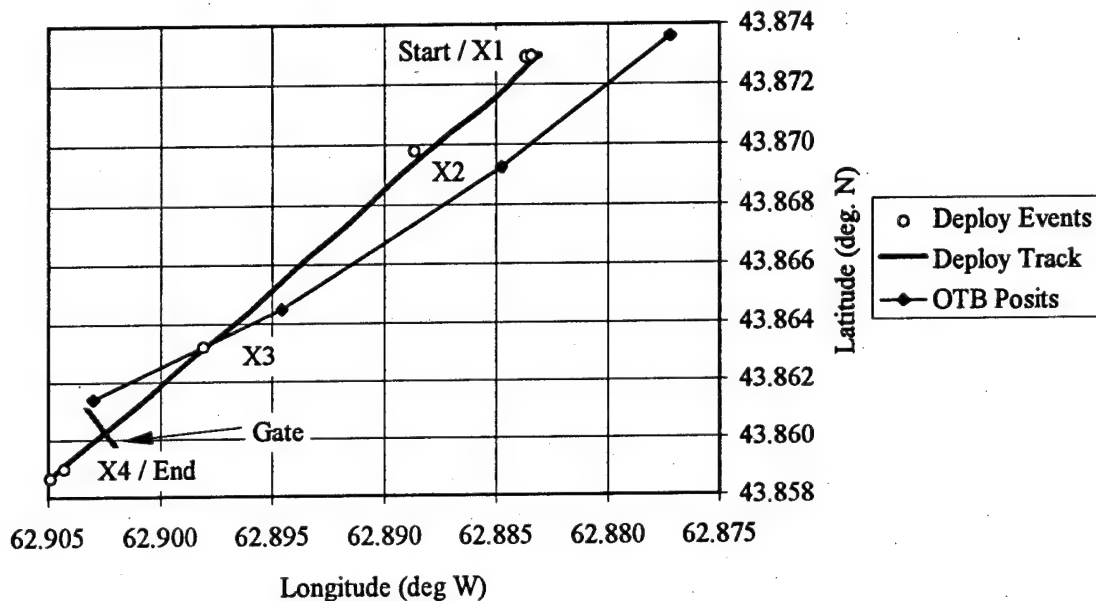
Figure 6 - Deployment 1 GPS data and transponder bottom positions

In Fig. 6, the track of the ship as the array was being paid out is depicted (the thick line starting in the upper right hand corner). Also shown are the positions when each transponder was extracted from the array frame (marked "Deploy Events" X1 through X4). An approximate gate position is shown based on GPS readings as the ship passed through the gate. Finally, the measured bottom positions of each transponder are indicated.

A greater insight into the ship's deployment motions can be obtained by analyzing the ship's speed over ground (SOG) and course over ground (COG) during the time of deployment (Fig. 7). It can be seen that for the first two minutes of the deployment the ship was essentially drifting in an easterly direction as the zodiac prepared the recovery line. This eastward drift was in agreement with the current profile shown in Fig. 5. At approximately 16:13:45 the ship started to accelerate to it's top speed while turning around to the south west to pass through the gate. A top speed of 12.5 knots was achieved after accelerating for roughly five minutes, and this speed was maintained until the array was fully extracted.

Figure 7 - Deployment 1 speed and heading over ground

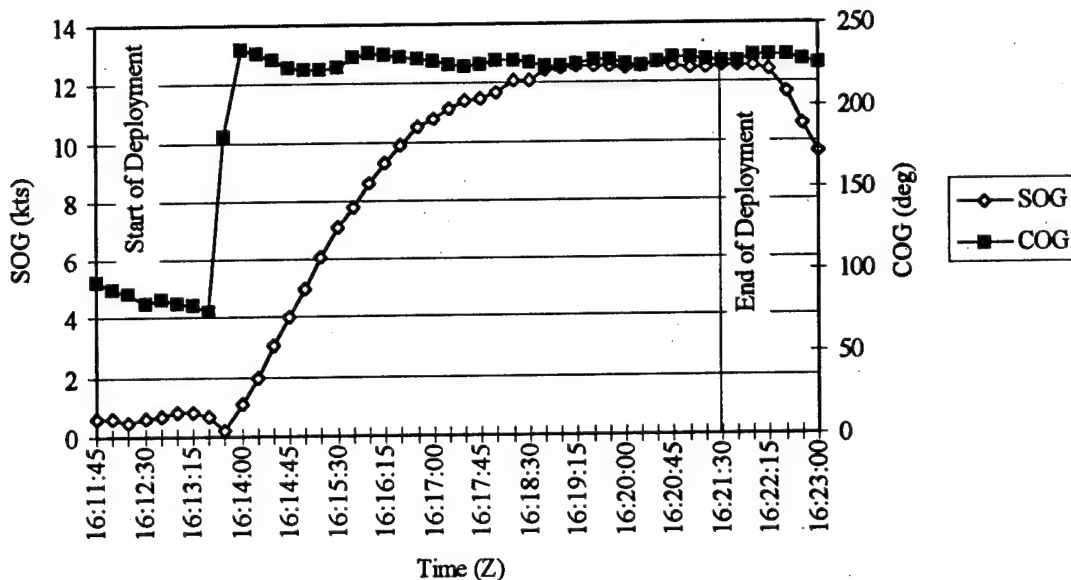A video camera mounted on a boom, aft of the ship, as well as a hand held video camera recorded the payout of the array. Although the camera on the boom had condensation on the lens limiting its clarity, the hand held camera was able to record some close up footage of the payout dynamics. As the ship came up to full speed the payout rate was estimated at 20 ft/s. There were no snags or tangles during deployment, but the inter-array line did cut through the disposable foam ADL holders mounted on the large bobbins. This did not appear to cause any problems.

The depth history of the ADL units from deployment 1 are shown in Fig. 8. ADL positions 6, 7, and 12 (corresponding to the positions shown in Fig. 1) are indicated on the chart. These data show a smooth and steady descent with most of the nodes arriving on the bottom at close to the same time approximately 45 to 50 minutes after the start of deployment. The two ADL's mounted on the inter-array line, positions 6 and 7, arrived 10 to 15 minutes later. This was expected because of the lower wet weight of the inter-array cable and drag amplification due to cable strum. Bottom arrival times and corresponding ADL positions on the array are given in Table II. The number 5 ADL was not functioning after recovery. During the set up before deployment two ADL's were placed at position 12 and a dummy unit was attached to position 8. This is reflected in Table II.
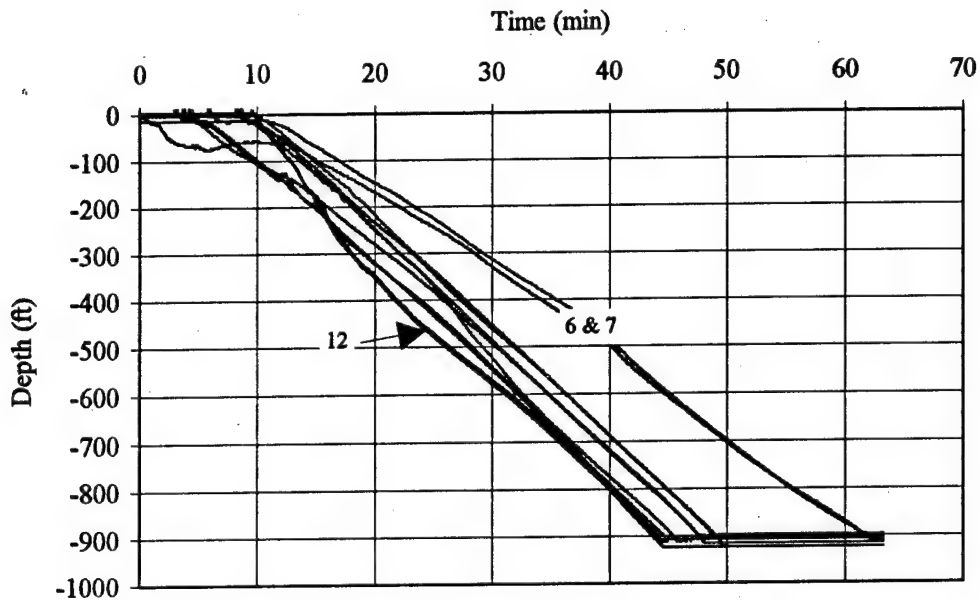
Figure 8 - Deployment 1 ADL depth histories.

ADL Position (see Fig. 1)	Time to Bottom (min)
1	44.57
2	47.43
3	45.70
4	44.60
5	*
6	62.17
7	61.83
9	48.07
10	49.73
11	48.97
12	44.10
12	44.13

Table II - Deployment 1 ADL bottom arrival times

About an hour after the deployment of the array, a towed projector was lowered into the water and the transponder positions on the bottom were measured by interrogating the transponders and recording the response. The results of that analysis are shown in Fig. 6, marked "OTB Posits". As expected from the current profile, the array shifted towards the east at the start (position X1), but the opposite end, X4, moved northeast, missing the gate during the descent. This may have been due to a shift in the current profile near X4. The distance between X1 and X2 indicated the on the bottom array length for the first array. The initial distance was 2400 feet, while the transponder

measured distance on the bottom was 2540 feet, giving an average spacing of 159 feet as opposed to 150 feet. The calculated distance for the second array was 2450 feet for an average spacing of 153 feet. It is unlikely that either array stretched that much; the error can be attributed to the accuracy of the transponder positioning system (± 15 feet per transponder), variations in the length of the cable wrapped on the bobbins (estimated at ±1 feet per bobbin or ±16 feet per array) and additional sources of error such as depth and sound speed profile variations. Drag on the inter-array cable caused the arrays to move 640 feet toward each other during descent, so that the spacing between the arrays was 3110 feet.

Deployment 2 - 27 October 1995

The second deployment began early in the afternoon on the 27th. The skies were clear and the seas and wind were extremely calm. Deployment began smoothly, and the first sub array was extracted without incident. The inter-array ADL mounts were ripped off as in the first deployment, but again this did not affect the deployment. As the third transponder was pulled into the water, the line connecting the transponder with the first array bobbin of sub array 2 pulled taut around the bobbin and several wraps of both the outer and inner cable layers were freed. The array cable tangled, eventually jammed, and the run had to be stopped. Analysis of boom camera footage of the deployment indicated that there was not enough service loop length between the transponder and first array bobbin. This permitted the cable to be pulled taut around the body of the bobbin instead of allowing the cable to clear the bobbin and start to pull from a position aft of the ship.

Deployment 3 - 27 October 1995

Preparations for the third deployment started immediately after the second deployment was aborted. The weather continued to be optimal; however, the sun was beginning to set at the start of the deployment, and the deployment ended in darkness. Because of the tight time constraints imposed by the late start, ADCP readings were taken after the array was off board. Current velocity measurements were taken at five sites along the deployment path. As with the data for deployment 1, the time averaged data from each site were consistent and were again averaged over the five sites. The averaged data are shown as the lines with markers in Fig. 9. The fitted data are indicated by the smooth lines. Again a negative east current is west and a negative north current is south. The current was strongest near the surface in an east northeast direction. The velocity of the current decreased with depth nearing zero at 500 feet. There was a small westerly current that peaked at slightly more than 0.1 ft/s at 700 feet then decreased to zero at the bottom.

Depth readings taken during deployment 3 indicated a very flat bottom with an average depth of 885 feet. The NADAS GPS readings and speed and heading data are shown in Figs. 10 and 11 respectively.
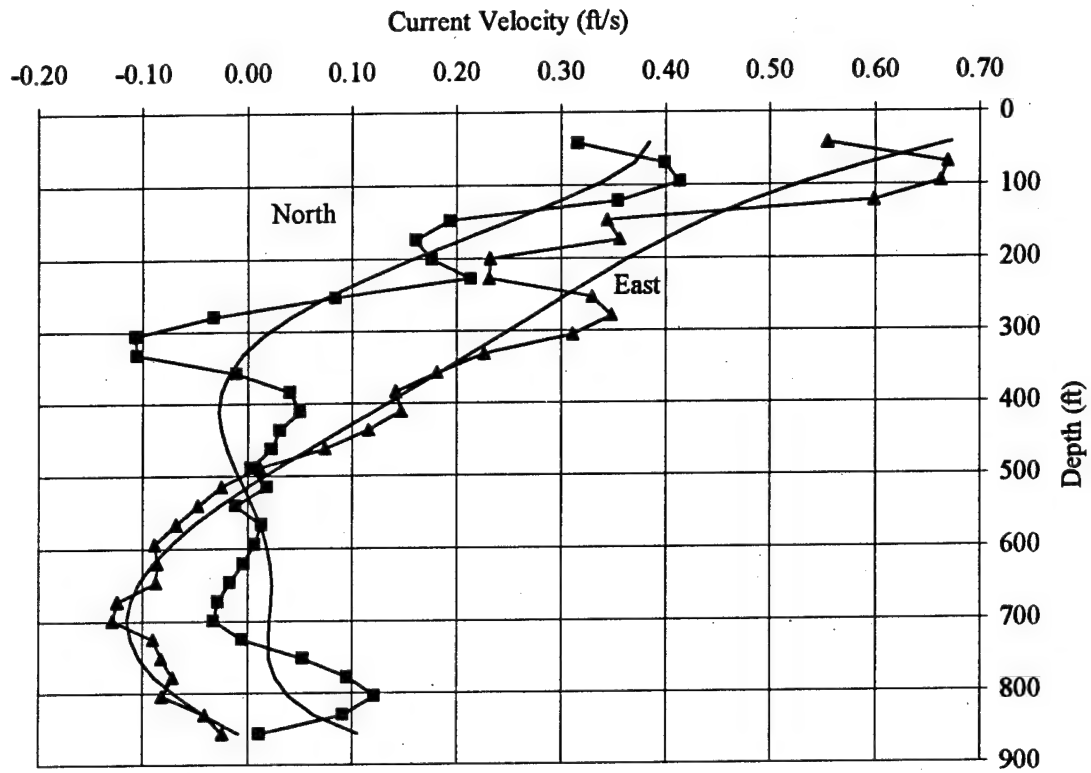
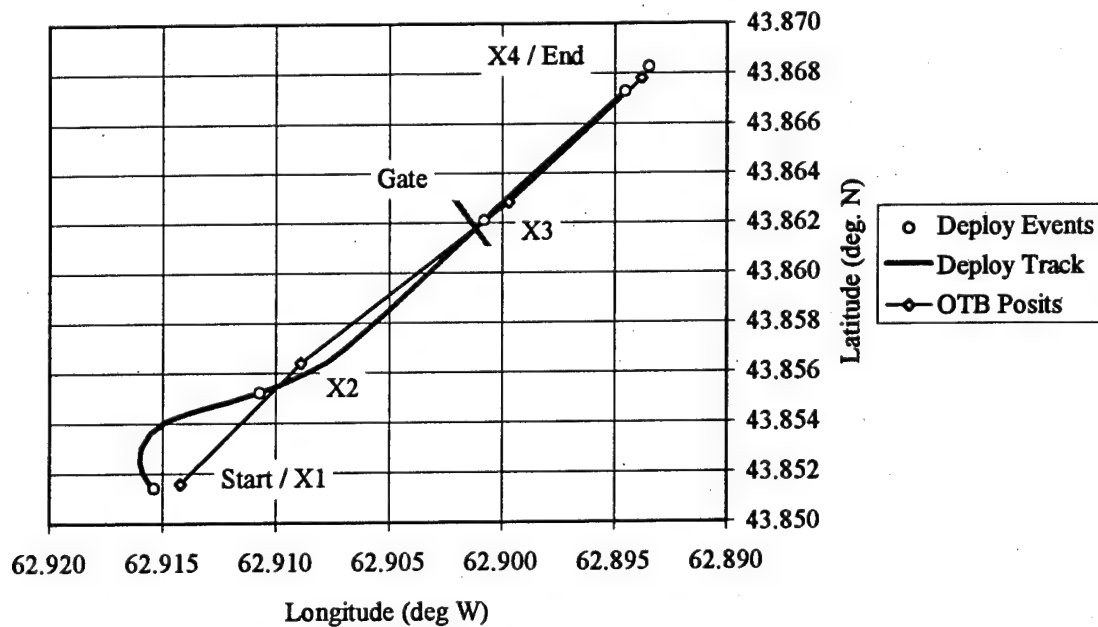Figure 9 - Deployment 3 current velocity profiles

Figure 10 - Deployment 3 GPS data and transponder bottom positions

Deployment 3 started on the opposite side of the gate from deployment 1, and the ship headed in a northeast direction as the array was paid out. During the initial stages, while the zodiac was setting the recovery moor, a cable tangle occurred while handing the cable to personnel aboard the zodiac. While this problem was being fixed, the Quest was blown to a northwest orientation. This made it necessary for the Quest to turn 90 degrees during the deployment of the first sub array in order to pass through the gate. Payout then continued without incident. The positions where the transponders were deployed are marked X1 through X4 ("Deploy Events" in Fig. 10). X1 and X2 were the ends of the first array and X3 and X4 were the ends of the second array. The gate was passed while the inter-array cable was still being paid out as planned. The initial turn and subsequent northeast track is evident in Fig. 11, as the ship's course over ground changed from roughly 350 degrees to 45 degrees where it remained steady. The speed over ground plot showed that after about three and a half minutes (from 21:26:30 to 21:30:00) the ship was able to accelerate to a steady speed of slightly more than 13 knots until the system was off board, at 21:34:00.
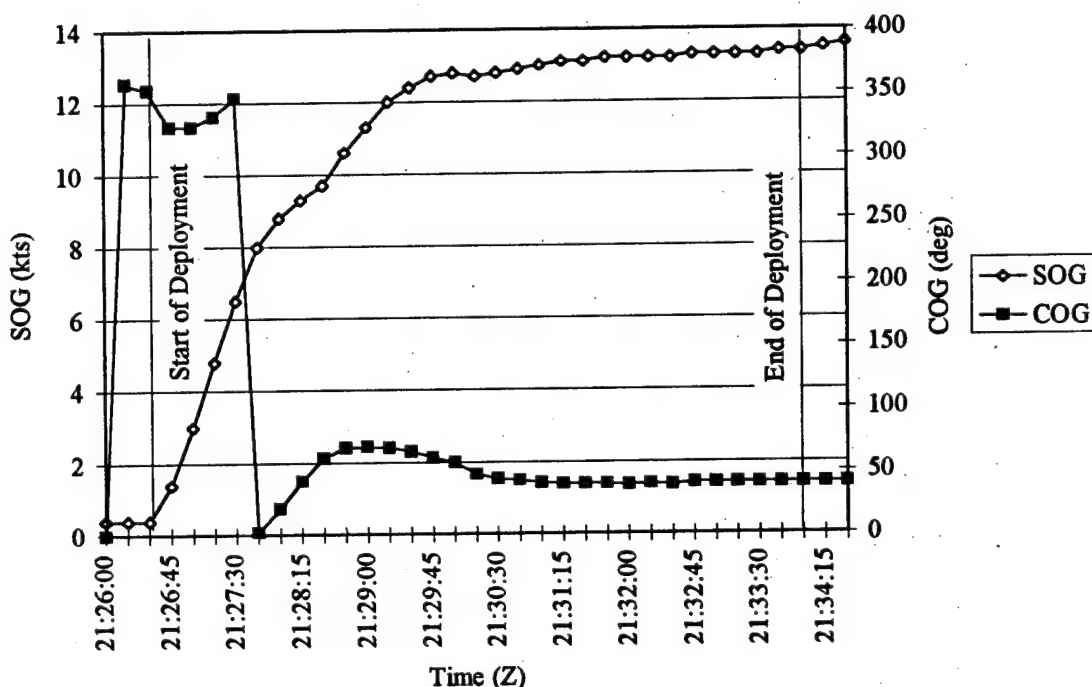
Figure 11 - Deployment 3 speed and course over ground

As with the first deployment, a video camera mounted on a boom aft of the ship and a hand held video camera recorded the payout. Because of the darkness during deployment, spotlights were used to illuminate the bobbins. Both videos indicated that the initial maneuvers of the Quest hampered payout because the cable was being pulled off at a severe angle. However, no catastrophic payout problems occurred. The bobbins were

designed to pay out cable from a very shallow angle, and after the ship was able to maintain a constant course, the payout was smooth.

Fig. 12 and Table III summarize the ADL data from deployment 3. Fig. 12 plots the ADL depth histories. Some of the node positions of interest are indicated by the position number intersecting the depth history line or, in the case of position 12, a number with an arrow pointing to the depth history line. In contrast to deployment 1 where most of the array units arrived on the bottom between 44 and 50 minutes, arrival times for deployment 3 ranged from 35 minutes to 45 minutes.
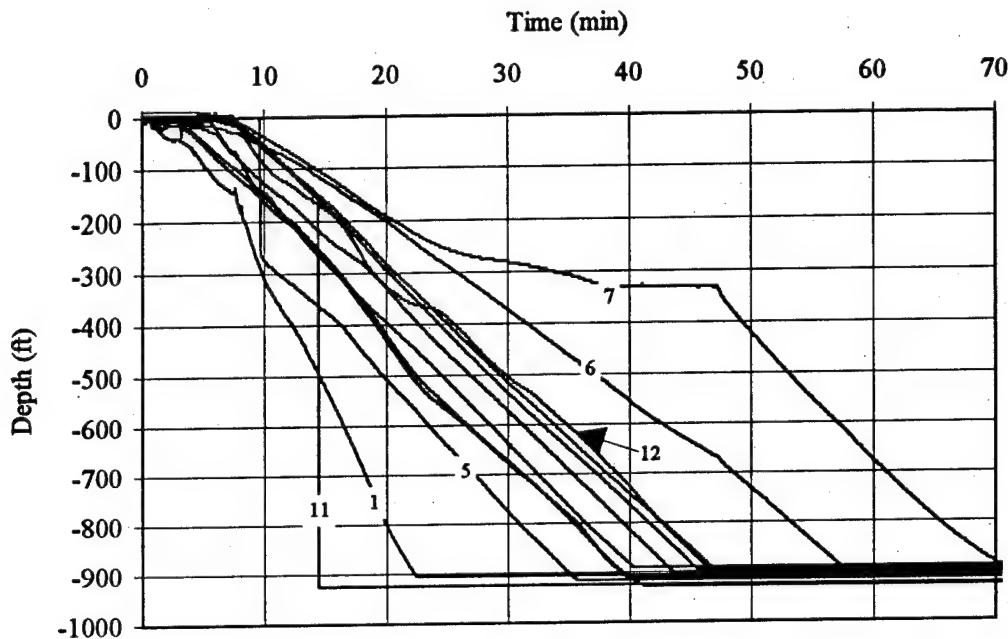
Figure 12 - Deployment 3 ADL depth histories

According to Fig. 12, the ADL in position 7 slowed considerably and eventually hovered at around 330 feet for ten minutes before descending to the bottom at a constant rate. It is unclear whether this was an actual physical phenomenon or if the timer in the recording device malfunctioned. Another interesting point arises from the deployment 3 depth history chart: the units closest to the parachutes, positions 1 and 12, have markedly different descent velocities. This is indicated by a difference in slope in the depth history lines and in the bottom arrival times (Table III). The same two positions in deployment 1 arrived on the bottom at roughly the same time, 44 minutes. In deployment 3, position 12 hit the bottom at 46 minutes, however position 1 took only 22.5 minutes to reach the bottom. Inspection of Fig. 12 shows that the position 1 ADL was descending during payout suggesting that the parachute was released before payout was concluded. It is possible that the parachute did not deploy properly. One reason for this may be due to the earlier mentioned tangle in handing off the line connecting the parachute with position 1.

In addition to ADL 7, two units had problems recording data. The ADL at position 11 (see Fig. 1) recorded depth data for 14.4 minutes to a depth of 151 feet

before a leak caused the unit to fail. The electronics in the position 5 ADL had to be changed at the last minute and an initial calibration could not be performed. As a result, the unit did not sense a change in depth until 265 feet (9.7 minutes after deployment started). This, however, had no bearing on the arrival time values.

ADL Number (see Fig. 1)	Time to Bottom (min)
1	22.47
2	41.13
3	43.50
4	40.27
5	35.60
6	57.83
7	70.00
8	39.70
9	45.53
10	47.23
11	*
12	46.33

Table III - Deployment 3 ADL bottom arrival times

Fig. 10, in addition to showing the surface track of the ship, and the transponder off board locations, indicates the transponder bottom positions, marked "OTB Posits", as determined by projector interrogations and transponder locator software. As noted earlier, each transponder is marked X1 through X4. According to the data, there was very little lateral movement by the array during it's descent from the surface deployed position. The length of array 1 on the bottom, the distance between X1 and X2, was 2252 feet for an average element spacing of 141 feet. Array 2 stretched out to 2382 feet on the bottom achieving an average element spacing of 149 feet. The short length of array 1 may have been due to the 90 degree turn taken by the ship at the start of deployment. As expected, the distance between the two sub arrays, the inter-array cable, was considerably less than its original length.

Computer Simulations

SEADYN is a general purpose finite element model that simulates the hydrodynamic response of various configurations of cable and/or truss type systems. There is a great deal of flexibility and capability built into SEADYN, reflecting the intention of the developers for it to be a hydrodynamic model that could be used with confidence in any situation. Simplex truss type elements as well as catenary line elements can be used to represent the system to be modeled. Bodies can be added in a simple lumped mass configuration, or a six degree of freedom rigid body, such as a ship, can be connected to the system. Cable laying payouts, as well as moored systems, free floating systems and underwater structures, have been successfully modeled by SEADYN[6,7,8]. Various solution methods are available for static and dynamic problems in both the time and frequency domain.

SEADYN Modeling Set-up

The inputs to SEADYN for the deployment test simulations were based on the physical parameters listed in Table I. Complete input file listings for deployment 1 and 3 simulations can be found in Appendix A. Element lengths were set to 150 feet corresponding to the array element spacings for a total of 61 elements and 62 nodes. Simplex element types that cannot support compression were used. The drag of bodies such as ADL's, dummy units and transponders was governed by the SEADYN default drag functions for cylindrical bodies. The parachute was modeled as a spherical body with a variable diameter, D. The drag area of the parachute used during the trial was known from drag tow tests conducted earlier[10]. The SEADYN drag coefficient was set equal to this known drag area of the parachute,

$$(C_d A)_{measured} = (C_d)_{SEADYN}. \tag{1}$$

This modeling strategy used the parachute diameter to vary the effective area of the parachute, thus modifying the parachute drag. The effective area, A_{eff}, was defined such that

$$A_{eff} = \frac{\pi}{4} D^2. \tag{2}$$

Therefore, the total drag area used by SEADYN was

$$(C_d A)_{SEADYN} = A_{eff} (C_d A)_{measured}. \tag{3}$$

Cable drag coefficients were another unknown during the initial preparation of the model. Cable drag could be greatly amplified by cable strumming (explained in more detail below) during the array descent, and this effect could be different for the array line versus the inter-array line. From past experience, cable normal drag coefficients could range between 3.3 and 1.7.

Water depth was input as a constant according to the NADAS average depth soundings recorded during the cable extraction. The curve fitted current data shown in Figs. 5 and 9 for deployments 1 and 3 respectively were input as a flow field table with 10 points of depth vs. x (east) and y (north) velocity. Between the points in the table, linear interpolation was performed by the model. For all cases the sea state was assumed zero.

Simulation of the deployment took place in two stages: a cable extraction sequence and a descent stage. The cable extraction portion used an external file containing the NADAS GPS data transformed into global coordinates (starting at 0,0,0) to govern the movement of the ship. As the ship moved along this track, cable was pulled from the ship. The first node, considered the end at the zodiac, was fixed in three dimensions throughout the cable extraction stage for deployment 1 and free to move in any direction for deployment 3. The difference in constraints for the first node was due to the observations made from the ADL depth histories of each deployment. Payout rate was controlled by a nine entry time function table. By assuming the line in the water has a catenary shape, the payout rate function was calculated using the catenary equation[11]

$$X_P = 2 * \frac{T_0}{w_C} \sinh(\frac{w_C X_{S1/2}}{T_0}) \hspace{3cm} (4)$$

where

X_P is the line length,
T_0 is the tension at the origin,
w_C is the average weight of the line in the water,
$X_{S1/2}$ is the horizontal distance from the origin (from NADAS data).

Fig. 13 provides an illustration of the various parameters in the equation. The tension at the origin is assumed constant, as the cable angle is zero by definition and the horizontal tension in a cable catenary is constant. All values of the equation are known in time except for the line length in the water and tension at the origin. An iterative solution was performed over the cable extraction period by varying the tension and having a goal of 9150 feet for the line length at the end of the run. The rate of payout was then calculated by simply dividing the length in the water by the time interval. The solution for deployment 1 is shown in Fig. 14. For comparison, the ship speed for the same time is indicated. The payout rate was necessarily greater than the ship's speed because the sag inherent in a catenary shape meant that more line was in the water than the distance traveled by the ship. The same procedure was used for deployment 3 with similar results.
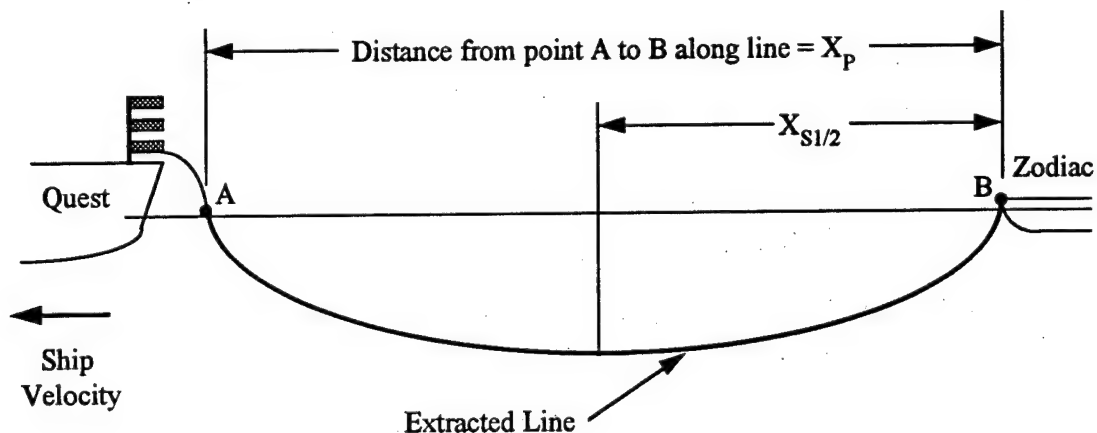

Figure 13 - Illustration of parameters used for payout rate determination.

After the cable extraction stage was completed, the node at the zodiac end, node 1, and the final payout node, node 62 were set free to move in any direction. The dynamic simulation continued until all the nodes reached the defined bottom.
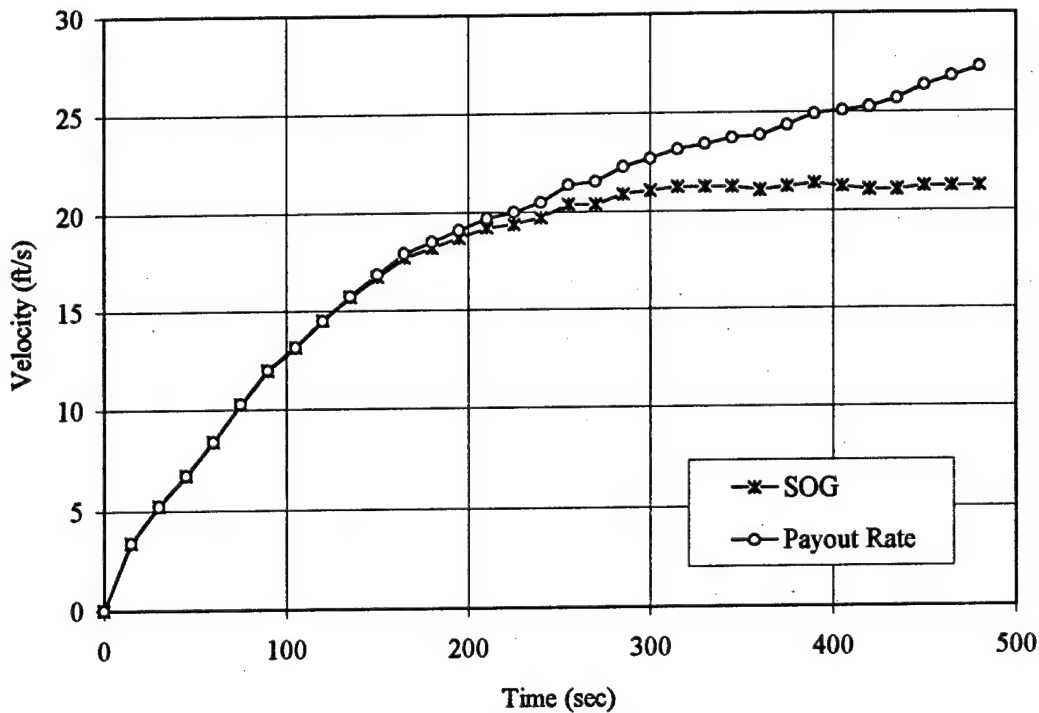
Figure 14 - Deployment 1 speed over ground and payout rate comparison

SEADYN Modeling Results

Multiple simulations were run for deployments 1 and 3. Four parameters were varied for each run: normal C_d for the array cable and the inter-array cable, and the parachute effective area of the zodiac end and the payout platform or Quest end. The cable C_d's ranged from 1.7 to 3.3 to account for drag amplification due to strumming, and the parachute effective areas were varied from 1.0 to 0.196. Simulation results were compared to the experimental results in terms of the descent characteristics, on the bottom arrival times, and bottom configuration.

For deployment 1, a simulation using an array C_d of 2.1, an inter-array C_d of 3.3, and effective areas of 0.442 and 0.785 for the zodiac and Quest parachutes respectively had the most favorable results when compared to the experimental results. The depth histories from this simulation are shown in Fig. 15, and Fig. 16 shows the final bottom position with respect to the deployment track.

Figure 15 - Deployment 1 simulation depth histories

Figure 16 - Deployment 1 simulation bottom positions

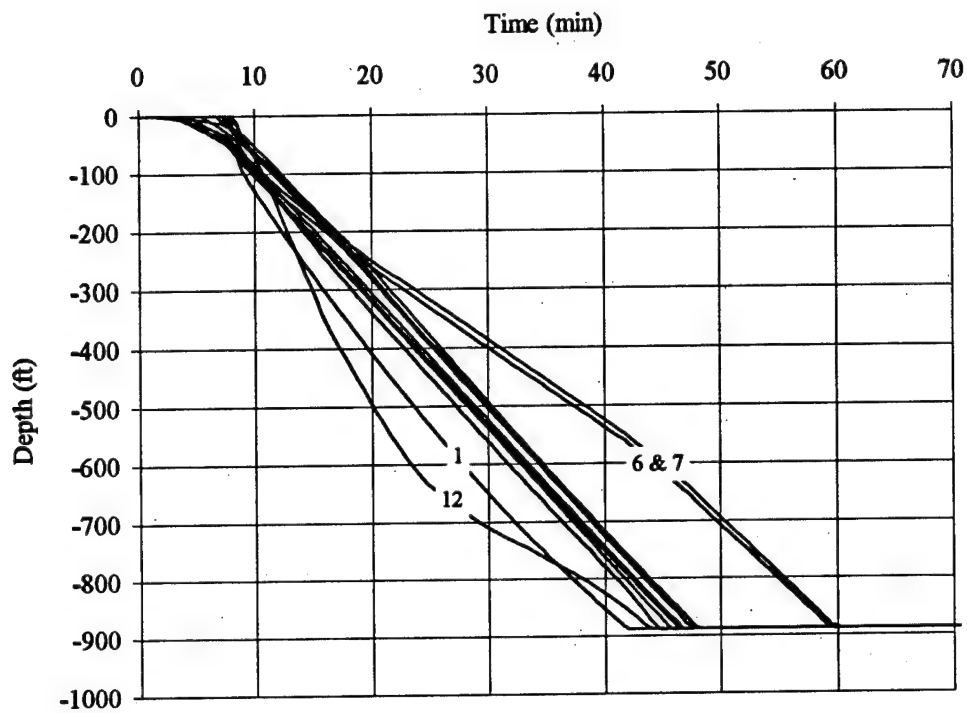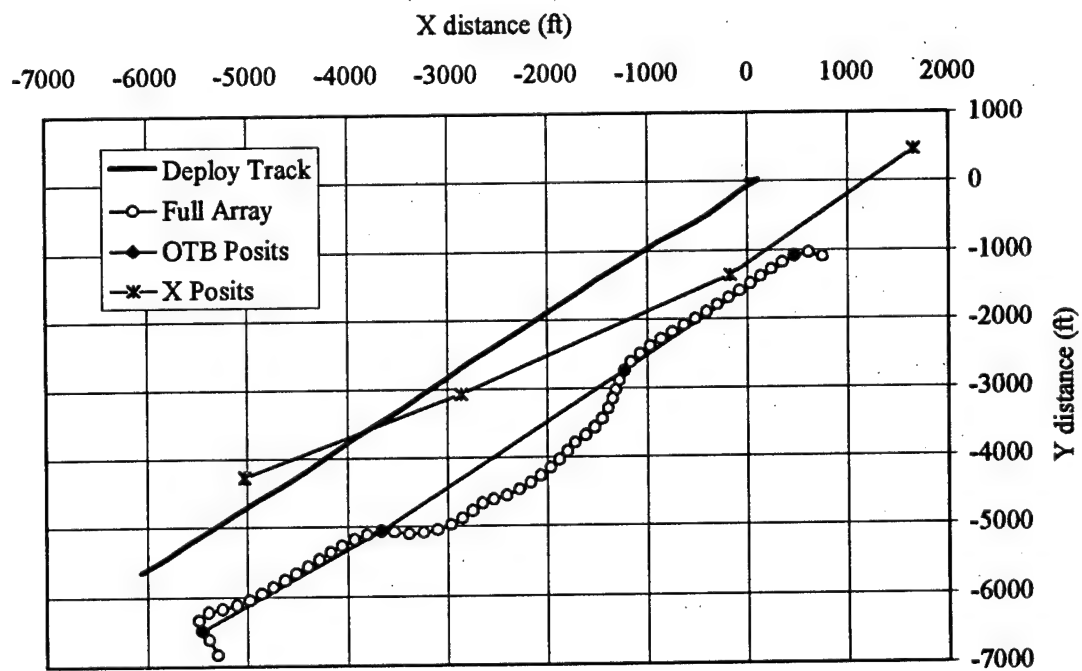In Fig. 15, the two inter-array nodes, 6 and 7 (selected node positions are indicated by the position number intersecting the depth history line), were seen to arrive on the bottom roughly 10 to 12 minutes after the array nodes. Node 12, adjacent to the Quest end parachute, descended at a fast rate for the first 500 to 600 feet, then decelerated before reaching the bottom. The array nodes, between the parachute and inter-array nodes, arrived on the bottom essentially at the same time after a near constant rate descent.

The bottom positions from the simulation of deployment 1, marked "Full Array" in Fig. 16, indicated a southeast drift from the deployment track, marked "Deploy Track" in Fig. 16, during descent. The measured transponder locations on the bottom are shown for comparison, marked as "X Posits". Except for a slight bow at the end of sub array 2, the array sections arrived on the bottom in a co-linear fashion. As expected, drag on the inter-array line caused the two arrays to move toward each other roughly 400 feet placing the two arrays 3350 feet apart. Fig. 17 plots element spacings for the two sub arrays. Full 150 foot spacings measured from node to node were achieved for all elements of both sub array 1 and 2.
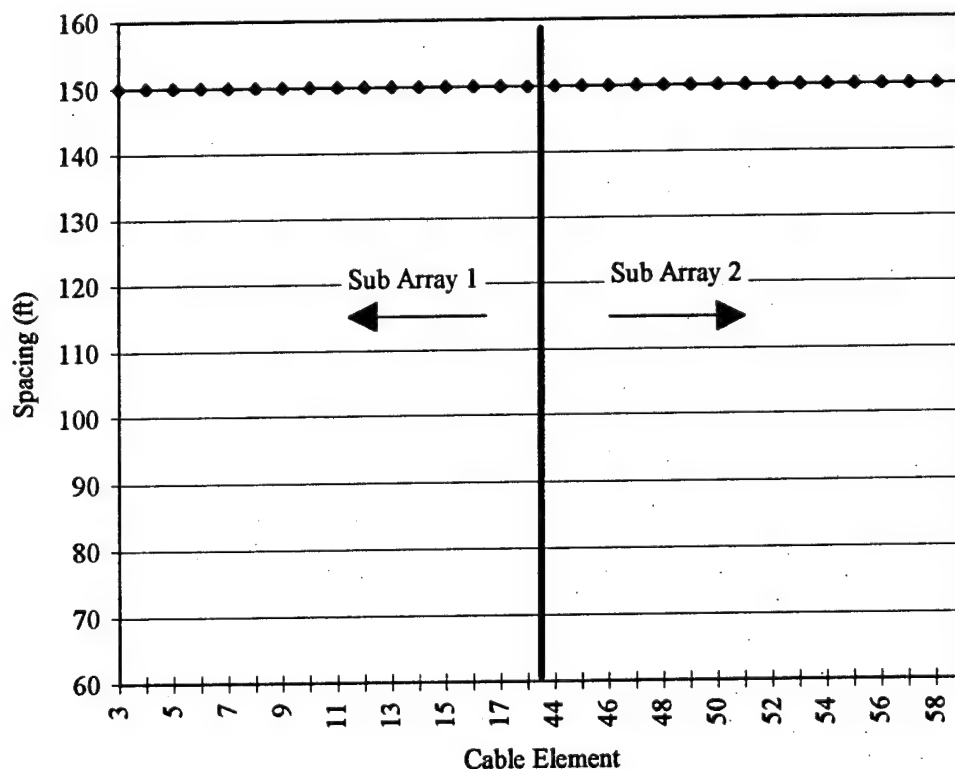
Figure 17 - Deployment 1 simulated element spacings on the bottom

A three dimensional snapshot plot of the system descending in 60 second intervals is shown in Fig. 18. The stationary zodiac end is on the right had side of the plot and the Quest end is on the left. The top line is the position of the split array at the end of payout. The presence of the two relatively heavy ADL units on the inter-array line forced the line to assume a three humped shape. The arrays descended in a relatively flat orientation due

to the drag of the parachute on one end and the inter-array cable on the other. The reduced spacing observed in Fig. 17 is evident in Fig. 18. Near the end of the descent, the array 2 parachute end nodes (left hand side) bunched together and arrived on the bottom with slack cable between the nodes.
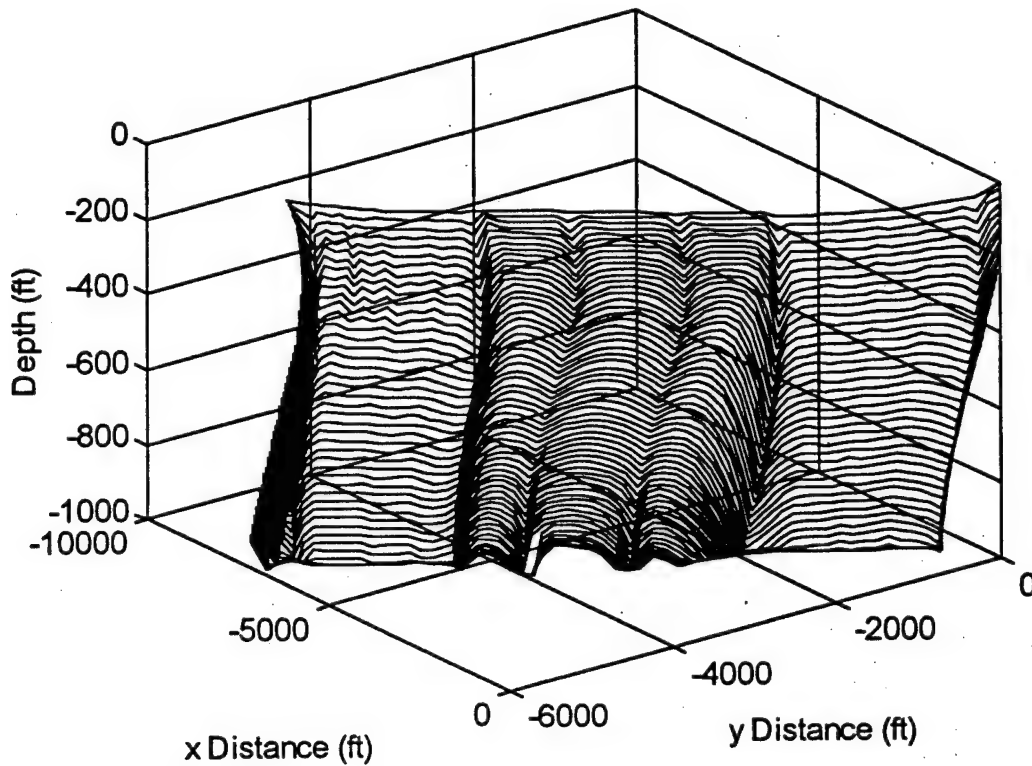
Figure 18 - Deployment 1 simulation 3-dimensional snapshot plot

The best results from the simulation of deployment 3 were achieved with the array $C_d = 2.4$, the inter-array $C_d = 3.3$, $A_{eff} = .283$ at the zodiac end and $A_{eff} = .785$ at the Quest end. In Fig. 19, the depth histories from this simulation are plotted. In this simulation the initial payout node, position 1, was free to move in any direction for the entire simulation.

Figure 19 - Deployment 3 simulation depth histories

As in the deployment 1 simulation, the inter-array nodes, 6 and 7, arrived on the bottom last after a slow, steady descent rate. The node at position 1 descended very quick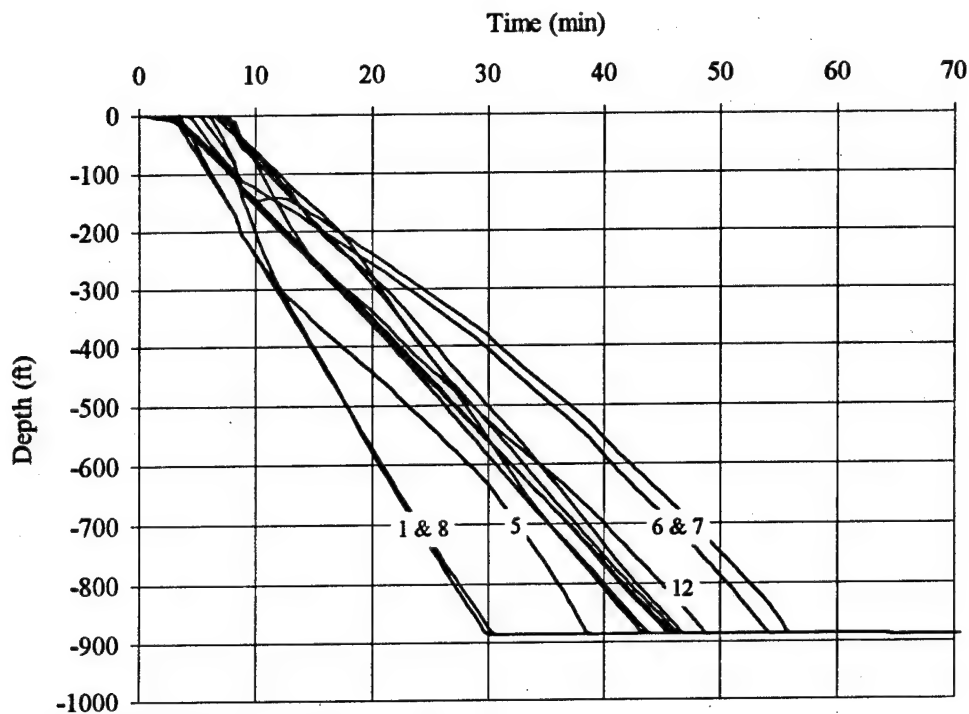ly and was the first to arrive on the bottom. This is consistent with the reduced drag area input for the first parachute. The last parachute, position 12, had more drag associated with it, and it descended at a much slower rate, arriving on the bottom almost 20 minutes after the first parachute. The position 8 node, the first transponder for the second sub array, had an almost identical depth history to that of position 1. The second transponder on sub array 1, position 5, had similar descent characteristics to the position one node for the first 10 to 12 minutes, at which point it slowed down to a speed similar to that of the inter-array nodes. Roughly 30 minutes into the deployment, corresponding to the bottom arrival of nodes 1 and 8, the dynamics of node 5 again changed and its speed increased slightly until it reached the bottom. The remaining nodes, all interior nodes of the sub arrays, descended in similar fashion arriving on the bottom within five minutes of each other.

A plan view of the deployment track and bottom nodal positions from the simulation of deployment 3 are shown in Fig. 20. The approximated deployment track used for the simulation, seen as a thick black line, was input as a tabular file (see Appendix A). The coordinates for the payout platform were input at one second intervals for the first 30 seconds, to insure solution convergence, and at 15 second intervals for the remaining deployment. The initial course correction is clearly seen. Despite a relatively high eastward surface current, the bottom position of the array, marked "Full Array", was not that far removed laterally from the deployment track. The array did travel parallel to

the deployment track, but this could be expected as the first end was released and the entire array was being pulled by the payout platform. For comparison, the measured transponder locations are shown, marked in Fig.20 as "X Posits". Both sub arrays lay on the bottom co-linear with respect to themselves, but they had differing orientations with respect to each other. The inter-array line bowed in the direction of the current and its spacing was reduced by 380 feet to 3370 feet.
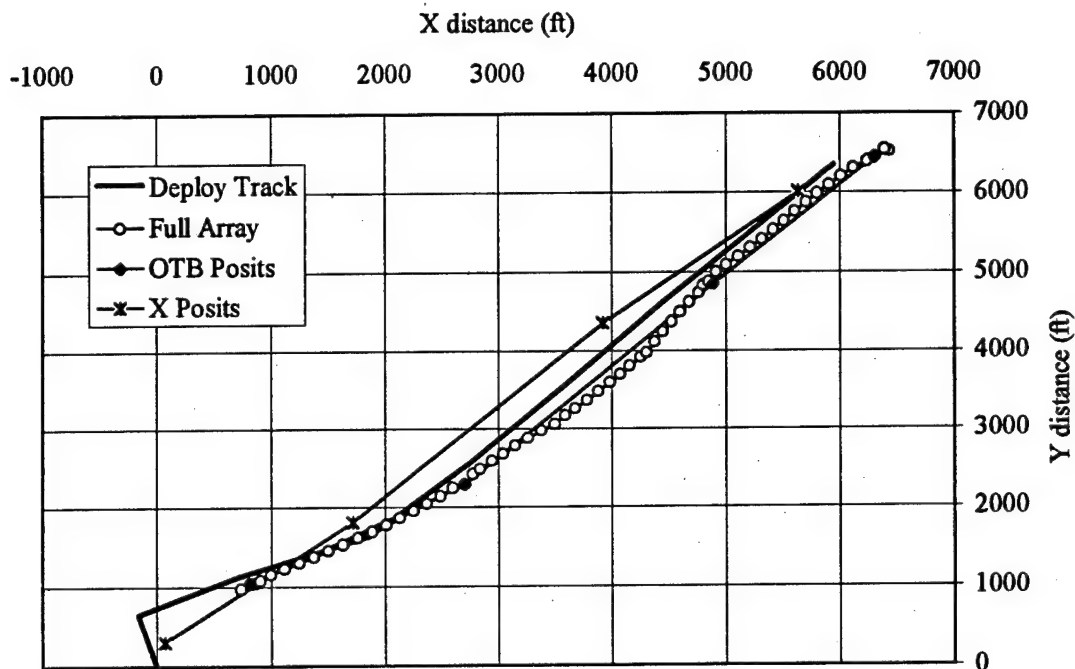
Figure 20 - Deployment 3 simulation bottom position

Element spacing for the sub arrays from the deployment 3 simulation are plotted in Fig. 21. Both ends of sub array 1 and 2 (transponder positions) had spacings less than the available 150 feet of line, but the interior nodes were stretched to the maximum spacing.
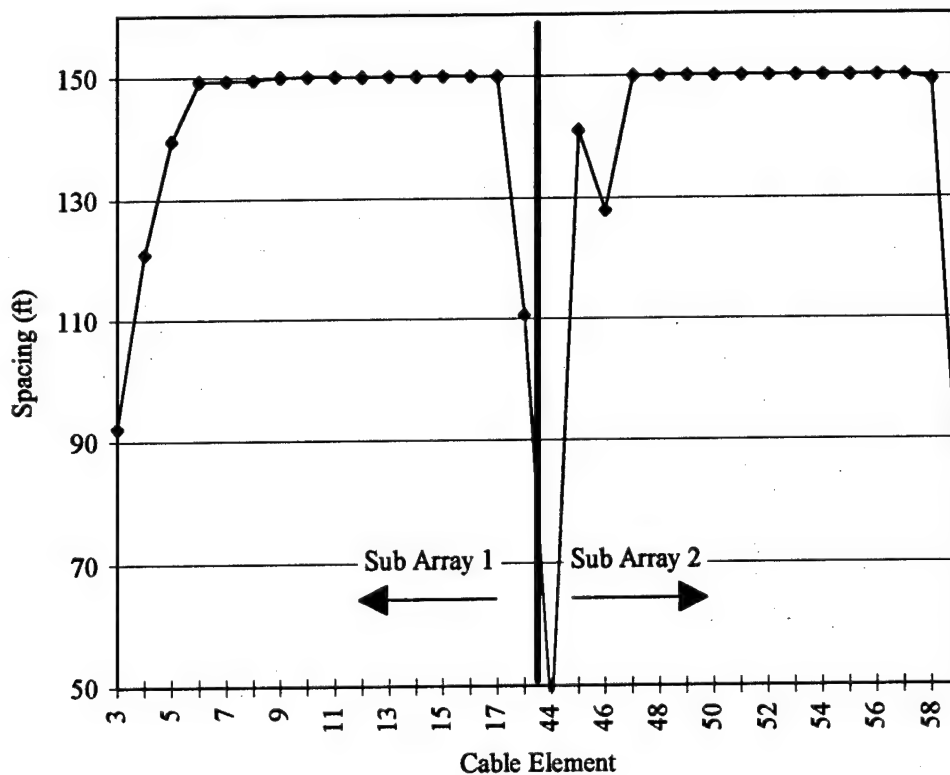
Figure 21 - Deployment 3 simulated element spacings on the bottom

Fig. 22 is a three dimensional snapshot depiction of the descending system from the deployment 3 simulation results. Deployment 3 started at the upper left corner of the plot (0,0,0), and the line closest to the top represents the positions of the nodes after the system has been fully paid out. The apparent increase in velocity, indicated by the change in spacing between the array position lines, is due to the perspective of the plot. The sub-array interior nodes descended in a flat stable manner and arrived on the bottom at roughly the same time. The inter-array line pulled both sub arrays toward each other and the positions of the inter-array ADL's can be seen as cusps in the inter-array line in Fig. 22. ·Near the bottom, sub array 1 and 2 nodes near the transponders can be seen to bunch together, resulting in the reduced spacings depicted in Fig. 21.
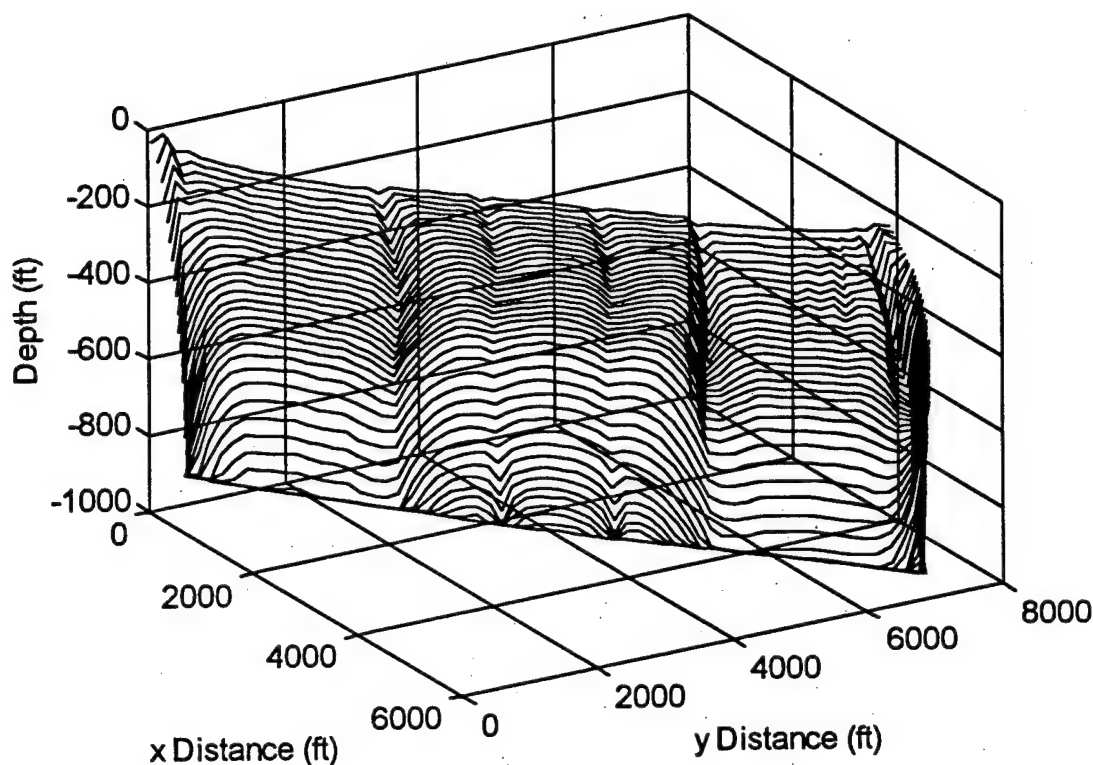
Figure 22 - Deployment 3 simulation 3-dimensional snapshot plot

Comparisons of SEADYN Results and Experimental Data

Direct comparisons between simulation results and experimental data can be made as to the bottom arrival times, depth histories, bottom locations and on the bottom spacings. In Fig. 23, the time it took for each ADL position to reach the bottom is plotted for the measured experimental data, "Measured TTB", and the SEADYN results, "SEADYN TTB". The figure shows very good correlation between the experimental data (no data from position 5 ADL and no ADL at position 8) and the simulation results. Again the two arrays arrived at roughly the same time, and the inter-array ADL's arrived 10 to 12 minutes later.

A comparison between simulated and experimental depth histories is made for selected positions in Fig. 24. The descent characteristics of the position adjacent to a parachute (1), an array position (10), and an inter-array position (6) are indicated. In general, the velocities of the simulated nodes were slower than the experimental velocities; however there is fairly good correlation for all three positions near the end of the descent.
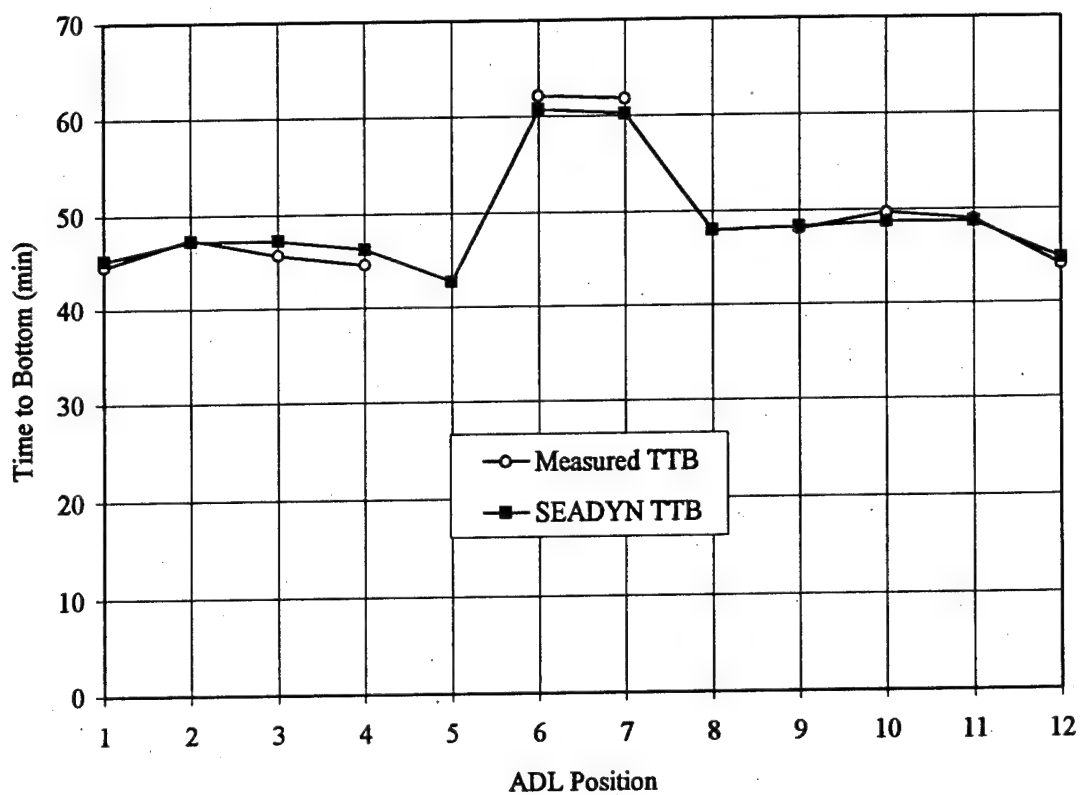
Figure 23 - Deployment 1 bottom arrival comparison
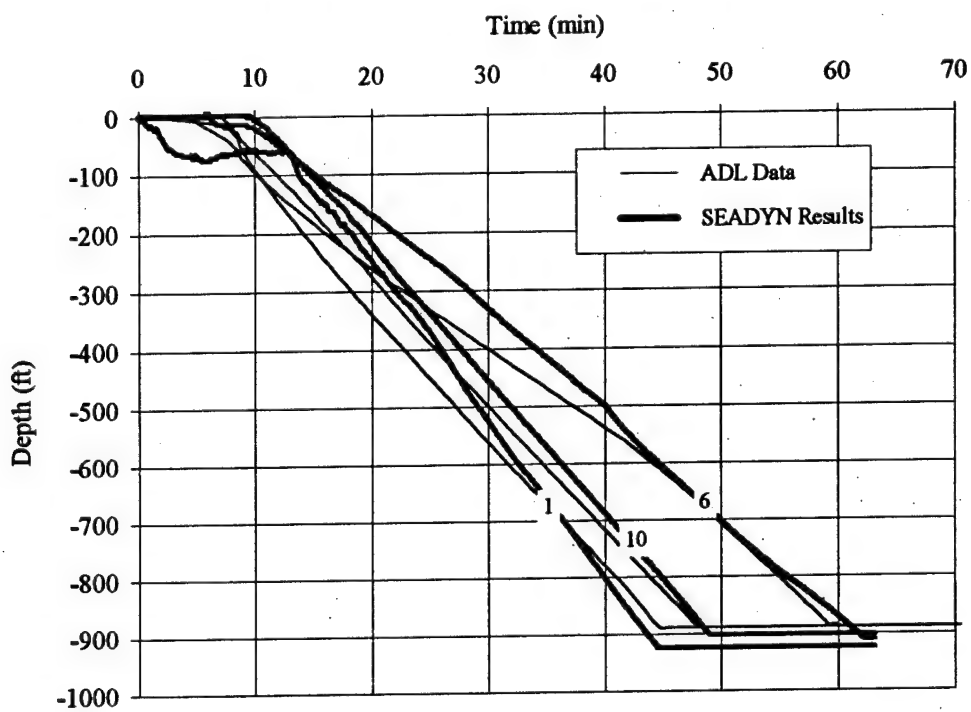
Figure 24 - Deployment 1 depth history comparison

Bottom spacing comparisons are made in Table IV. The average element spacings were calculated by dividing the distance between the transponders by 16 element spacings. The average element spacings for both arrays as calculated from the SEADYN results were ten feet less than those calculated from the transponder data, and the SEADYN inter-array spacing was 240 feet greater. Although Fig 17 indicated that the element spacings were 150 feet, the average spacing calculated here used the straight line distance between the transponders to allow for direct comparison to the experimental data. Any bowing of the arrays caused average element spacings to be less than the node to node distances.

	Experimental Data	SEADYN Results
Array 1 (X1 to X2) Distance (ft)	2540	2389
Array 1 Average Element Spacing (ft)	159 (calculated)	149
Inter-array Spacing (ft)	3110	3350
Array 2 (X3 to X4) Distance (ft)	2450	2285
Array 2 Average Element Spacing (ft)	153 (calculated)	143

Table IV - Deployment 1 bottom spacing comparison.

Another measure of the success of the modeling effort is to compare the orientation of the array on the bottom. In Fig. 16, the transponder measurements, labeled "X Posits", can be directly compared to the SEADYN results, "OTB Posits". The simulation did not duplicate the eastward motion of the X1 transponder (upper right on the plot) end nor the northeast motion of the opposite end. Instead, the entire array moved almost as a unit in a southeast direction. Both results, however, indicated similar orientations.

A comparison of the bottom arrival times from the experimental data and the SEADYN results for deployment 3 is shown in Fig. 25. The correlation between the two results is not as good as that for deployment 1. In general the SEADYN results were too slow to the bottom for the first parachute, sub array 1, while the position 8 transponder, and the inter array descended too quickly. Further reduction of the first parachute effective area and array cable coefficient of drag did not improve the results because of the influence this had on subsequent node dynamics. It should also be noted that the position 7ADL data was likely in error, see Fig. 12. The SEADYN results did, however, replicate the general trends seen in the ADL results. These trends were also evident in the depth history plot comparison, Fig. 26. The array node (10) and the inter-array node (6) show very good correlation with the experimental data. The parachute node (1) descends at a much slower rate than indicated by the ADL data at that position, as would be expected from the bottom arrival time results.
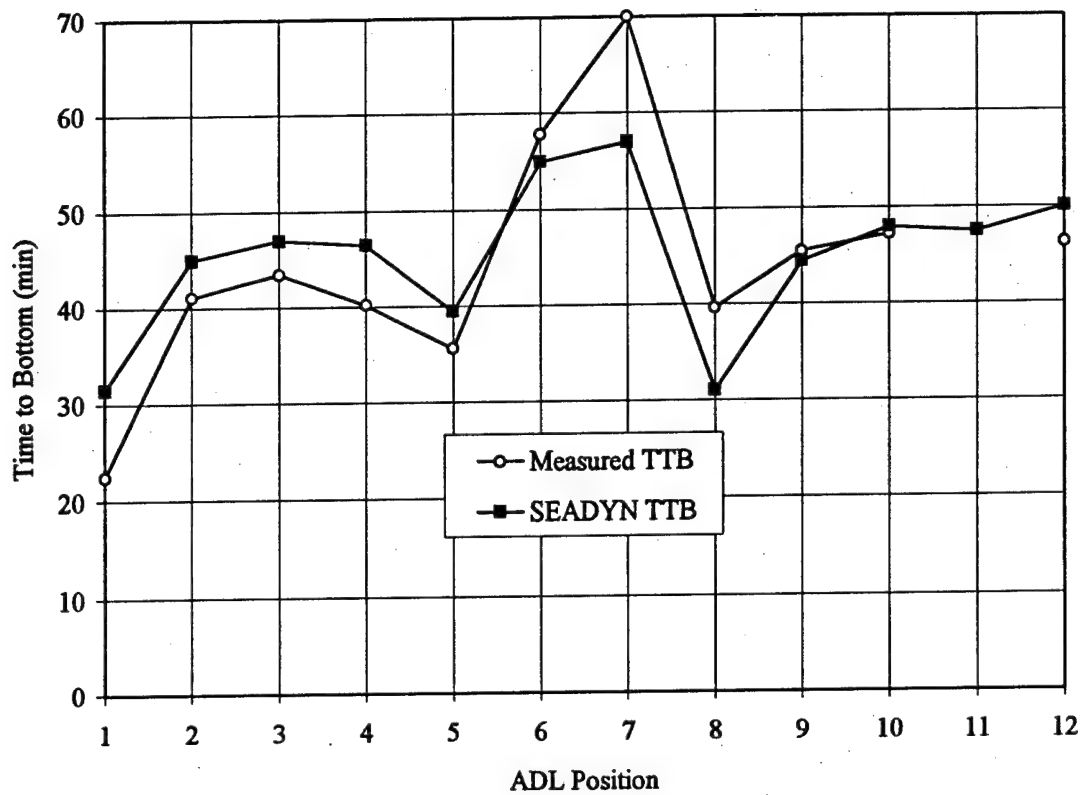
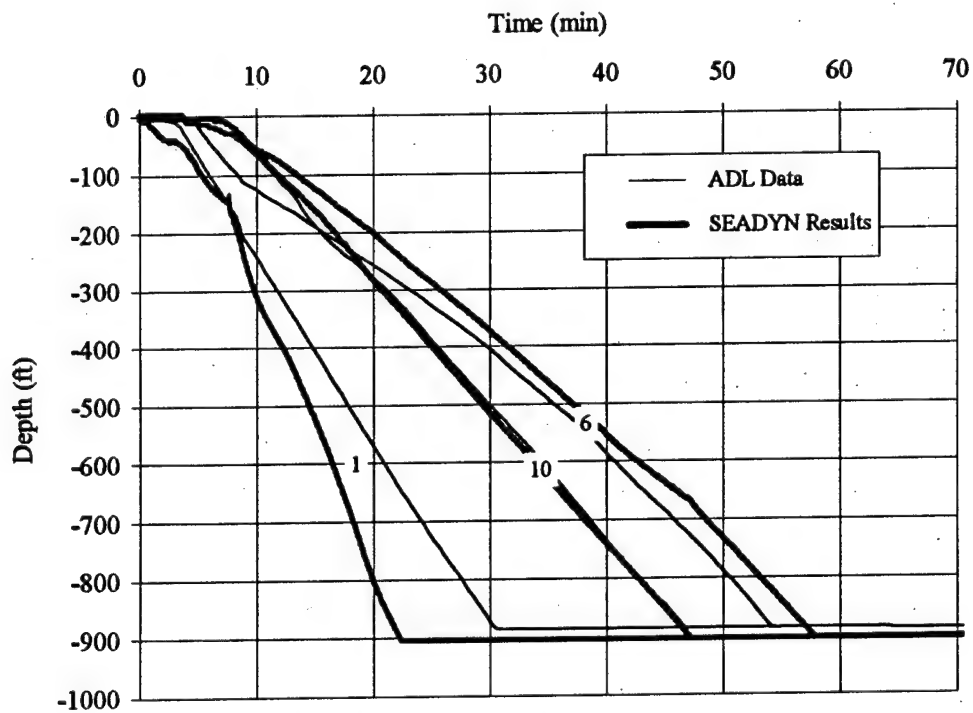Figure 25 - Deployment 3 bottom arrival comparison

Figure 26 - Deployment 3 depth history comparison

A direct comparison is made between the bottom locations from the simulation and the transponder measurements, Fig. 20 (same labeling convention as Fig. 16). Both sets of data show very little movement normal to the direction of the payout track. Although the exact location of the simulated and experimental arrays do not match, the shape and orientation are well correlated.

Table V gives a comparison between the experimental and simulation bottom spacing results. The average element spacing from the SEADYN simulation (calculated in the same way as for deployment 1) for the first array was the same as the experimental data from the transponders, 141 feet, and the inter-array spacing was different by only 12 feet. This excellent correspondence between experimental and modeled results did not continue for the second array. The experimental data indicated that the average element spacing was 149 feet, but the simulation results had an average spacing of 133 feet; however, as indicated above, this reduced spacing was seen at the elements closest to the transponders.

	Experimental Data	SEADYN Results
X1 to X2 Distance (ft)	2252	2253
Array 1 Average Element Spacing (ft)	141 (calculated)	141
Inter-array Spacing (ft)	3358	3370
X3 to X4 Distance (ft)	2382	2130
Array 2 Average Element Spacing (ft)	149 (calculated)	133

Table V - Deployment 3 bottom spacing comparison.

Conclusions from the Modeling Effort

Not only were the normal cable drag coefficients used in the simulations different for the array cable and the inter-array cable, they were higher than normally expected for cylindrical cables[12]. In order to achieve results that approached the experimental data, it was necessary to change the cable C_d values over several runs. It was hypothesized that the increase in drag was due to cable strumming. Over the years there have been many investigations into the effect cable strumming, also known as vortex shedding, has on the drag characteristics of cables.[13,14,15] These studies generally relate drag amplification to the natural frequency of the cable, the vortex shedding frequency, and physical cable parameters. An amplified coefficient of drag was calculated by curve fitting empirical data. The deployments discussed in this paper do not lend themselves to such an analysis. The cables have attached masses and the cable configuration between these masses is a catenary shape. The cable shape, and the resulting uneven distribution of normal relative velocity during descent, make accurate modeling of cable vibrations beyond the abilities of SEADYN. For these reasons, cable C_d could only be guessed at during the design stage. By using high and low values the problem could be bracketed, and the system could be designed with confidence; however the true cable drag could not be known beforehand.

The difference between the array and inter-array cable normal drag coefficients were due to the difference in diameter and the length of cable between the bodies. The array cable had a larger diameter and smaller spacings. A crude approximation can be

made by assuming a roughly equal velocity and tension for the two cables. This would mean the vortex shedding frequency for the array cable would be lower than that for the inter-array cable and the natural frequency of the array cable would be higher than the inter-array cable. It is possible that the inter-array cable was strumming over a greater region of the cable than for the array cable. This could cause the appearance of a higher C_d value for the inter-array cable. However, the validity of this analysis is in question until a more sophisticated strumming model is developed.

The position of the system on the bottom for deployment 1 as predicted by the model, Fig. 16, was a uniform displacement to the south east relative to the deployment track. This was not the same as the bottom orientation calculated from the transponder data shown in the same figure. The reason for this was two fold. One was that the current profile varied in time as well as space during the experiment. The current profile entered into the model was an average of current profiles taken at intervals along the deployment track before the deployment. The exact current conditions in time and space could not be accounted for exactly. The simplified current used in the simulation was considered a good approximation as reasonable agreement, considering experimental error, was achieved between the modeled results and the test data for both bottom arrival time and array spacings. The second cause of error was the incomplete understanding of the payout dynamics and topology. Payout rates were estimated by assuming a catenary in the cable during payout that was horizontal at the midpoint of the extracted length of cable (see above). This simplification allowed payout rates to be calculated over time, but it is by its nature an approximation giving rise to discrepancies between the simulated and experimental results.

The differences between experimental and simulated bottom spacings for the second sub array in deployment 3 were partially caused by the simulated payout rate. The rate was too high at the end of the payout. An examination of the tension history of the elements in the deployment 3 simulations showed that the final elements of the second array had zero tensions at the end of payout and very low tension throughout the deployment. This slack section of cable was never pulled straight by the parachute and the nodes were placed on the bottom with slack line between them. Because the zodiac end was released before the end of payout, the payout rate model (explained above) was partially invalidated.

Despite the addition of buoyant material to reduce the wet weight, the transponder and ADL combinations (positions 1, 5, 8, and 12) were heavy relative to the ADL or dummy units. In effect, the transponders drove the descent of the system. Bottom arrival times and depth histories indicate that the transducer positions descended quickly pulling the remaining system behind them and hitting the bottom first. Once the transponders were on the bottom they were essentially anchored. The array spacings were set even though all the array elements were not on the bottom. The reduced element spacings seen at the ends of sub array 2 from deployment 1 and sub array 1 from deployment 3 are the result. The arrays assume a flat shape during descent but can not fit in the space determined by the transponders.

In order to match the SEADYN results with the experimental results, a reduced effective area had to be used to model the parachutes. For both deployments the parachute at the zodiac, or position 1, had dramatically decreased effectiveness, while the

payout platform end parachute, position 12, was modeled with close to a 75% effective area. The probable cause of this lies in the difference between the deployment techniques for each parachute. The zodiac parachute was held at the surface for a period of time (for the entire deployment period in the case of deployment 1 and for the initial recovery line set-up time for deployment 3) before being allowed to descend. While on the surface, the parachute was subjected to wave motion, surface currents and winds. These phenomena could easily cause problems such as shroud lines tangling or getting caught above the canopy, and fouling with the recovery line. If the parachute was deployed under these conditions, its drag area would be reduced and this would be seen as a reduced effectiveness in the model. The parachute deployed from the payout platform was packed in a plastic bag. The bag and parachute were pulled off board and a length of line connected to the bag and the ship pulled the bag free from the parachute away from the boat. When the parachute was deployed it was away from the turbulence of the boat and beneath the surface effects. This would have allowed for a more effective deployment to occur.

ACKNOWLEDGEMENTS

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APPENDIX A- SEADYN Input Files

Deployment 1 SEADYN Input File

```
SEADYN analysis of GTP-9 Experiment Fall 95 - Deployment 1 ;
*Deployment #1 - 150 ft node spacing - Held at zodiac
*Black Cross parachutes - CdA=31.87 sq ft $
PROB;62,61,3,1          *Gravity direction Z
FLUI;0,1
LIMI
 1,0,1
 2,888,1,0,1            * Average deployment depth
LLOC
 1,1,62
 2,1,62
BODY
 1,0,.17,0.1875,0.5          *ADL
 2,0,.67,.5,1.167           *ADL + Transponder
 3,0,.22,0.1875,0.5          *Dummy unit
 4,2,1.3,.75,,1.            *Pos 1 PARACHUTE
 7,2,1.3,1,,1.             *Pos 62 PARACHUTE
 5,0,.5,.5,1.167            *Lone Transponder
 6,0,.84,.5,1.667           *Transponder + 2 ADL
MATE
 1,3,.011,0.00166,W7,1600,0,2000,1  *ARRAY LINE
 2,4,0.00517,0.0008,W7,450,0,2000,1 *CONN LINE
BLOC
 4,1                *PARACHUTE
 2,3                *1ST TRANSPONDER+ADL
 3,4,6              *DUMMY UNITS
 1,7                *ADL
 3,8,10             *DUMMY UNITS
 1,11               *ADL
 3,12,14            *DUMMY UNITS
 1,15               *ADL
 3,16,18            *DUMMY UNITS
 2,19               *2ND TRANSPONDER+ADL
 3,27               *C/L ADL 1
 3,36               *C/L ADL 2
 5,44               *3RD TRANSPONDER (no ADL dep 1)
 3,45,47            *DUMMY UNITS
 1,48               *ADL
 3,49,51            *DUMMY UNITS
 1,52               *ADL
 3,53,55            *DUMMY UNITS
 1,56               *ADL
 3,57,59            *DUMMY UNITS
 6,60               *4TH TRANSPONDER+ 2 ADL
 7,62               *PARACHUTE
DRAG
 1,2,.90,.85            *HYDROPHONES
 2,2,37.87          * Cross PARACHUTE CdN = CdA,
 3,2,2.1,.02            *ARRAY LINE (Strum Cd = 2.1)
 4,2,3.3,.02            *CONN LINE (Strum $c_d$ = 3.3)
NODE
 1,1,0,0,0
```

```
  2,1,0,0,0,2,2,2
 62,1,0,0,0,2,2,2
NGEN
 59,2,62                 * STRAIGHT LINE GEN
TFUN
 1,1,0,0,60,1,1      *60 sec ramp from 0 to 1 then const
 2,1,0,0,10,100,1      *10 sec ramp for 100 N tension
 3,6,0,615          *Ship's track from GPS during payout - NODMOV.TAB
 4,3,0,0,.1,
 60,8.44,
 120,14.46,
 180,18.36,
 240,20.10,
 300,21.82,
 360,22.35,
 420,23.00,
 515,23.97,0
FLOW
 1,2,0,.75,0,0,
 43,.669,-.043,0,
 121,.566,-.189,0,
 253,.593,-.461,0,
 358,.526,-.604,0,
 462,.341,-.546,0,
 568,.19,-.402,0,
 672,.05,-.285,0,
 803,0,-.096,0,
 900,0,0,0
PAYOUT
 1,2,1,150,60,10,1,1 *150'  mitosis length
ELEM
 1,1,2,,1
 18,18,19,,1
 19,19,20,,2
 43,43,44,,2
 44,44,45,,1
 61,61,62,,1
TABLE
 1,W11,1,27              *Nodal positions and element tensions
* 2,64,80,,64,79,W11,1
*DEAD
DYN
 SOLU,,,,.0125
 FIX,3,11,12,13                   *Fixed z motion at zodiac
 MOVE,-1,1,3,1  *, 1,3,1,1,3,1  *Motion of payout node read from a file
 CURR,1,1
 PAYO,1,4,1                  * Tabular TFUN from GPS to payout full array
 TIME,.001,525
 OUTP,,15,W15,1,15,1
DYN
 SOLU,,,,.001
 FREE,11,12,13,621,622,623
 CURR,1,1
 TIME,,3900
 OUTP,,30,W15,-1,30,1
END
```

Deployment 1 NODMOV.TAB File

Time	X (ft)	Y (ft)	Z (ft)
0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.50E+01	1.52E+01	2.65E-01	0.00E+00
3.00E+01	2.78E+01	9.28E-01	0.00E+00
4.50E+01	4.28E+01	3.57E+00	0.00E+00
6.00E+01	6.04E+01	5.72E+00	0.00E+00
7.50E+01	8.04E+01	8.89E+00	0.00E+00
9.00E+01	1.00E+02	1.28E+01	0.00E+00
1.05E+02	1.17E+02	1.70E+01	0.00E+00
1.20E+02	1.17E+02	1.20E+01	0.00E+00
1.35E+02	9.44E+01	-3.98E+00	0.00E+00
1.50E+02	5.39E+01	-3.45E+01	0.00E+00
1.65E+02	-5.29E+00	-8.59E+01	0.00E+00
1.80E+02	-7.69E+01	-1.58E+02	0.00E+00
1.95E+02	-1.63E+02	-2.50E+02	0.00E+00
2.10E+02	-2.69E+02	-3.63E+02	0.00E+00
2.25E+02	-3.96E+02	-4.90E+02	0.00E+00
2.40E+02	-5.47E+02	-6.17E+02	0.00E+00
2.55E+02	-7.21E+02	-7.48E+02	0.00E+00
2.70E+02	-9.06E+02	-8.93E+02	0.00E+00
2.85E+02	-1.10E+03	-1.05E+03	0.00E+00
3.00E+02	-1.30E+03	-1.23E+03	0.00E+00
3.15E+02	-1.50E+03	-1.41E+03	0.00E+00
3.30E+02	-1.70E+03	-1.61E+03	0.00E+00
3.45E+02	-1.91E+03	-1.81E+03	0.00E+00
3.60E+02	-2.12E+03	-2.01E+03	0.00E+00
3.75E+02	-2.34E+03	-2.21E+03	0.00E+00
3.90E+02	-2.57E+03	-2.42E+03	0.00E+00
4.05E+02	-2.79E+03	-2.63E+03	0.00E+00
4.20E+02	-3.01E+03	-2.85E+03	0.00E+00
4.35E+02	-3.24E+03	-3.07E+03	0.00E+00
4.50E+02	-3.46E+03	-3.29E+03	0.00E+00
4.65E+02	-3.70E+03	-3.51E+03	0.00E+00
4.80E+02	-3.94E+03	-3.72E+03	0.00E+00
4.95E+02	-4.17E+03	-3.94E+03	0.00E+00
5.10E+02	-4.39E+03	-4.16E+03	0.00E+00
5.25E+02	-4.63E+03	-4.38E+03	0.00E+00
5.40E+02	-4.87E+03	-4.59E+03	0.00E+00
5.55E+02	-5.11E+03	-4.80E+03	0.00E+00
5.70E+02	-5.34E+03	-5.01E+03	0.00E+00
5.85E+02	-5.58E+03	-5.23E+03	0.00E+00
6.00E+02	-5.81E+03	-5.45E+03	0.00E+00
6.15E+02	-6.05E+03	-5.65E+03	0.00E+00

Deployment 3 SEADYN Input File

```
SEADYN analysis of GTP-9 Experiment Fall 95 - Deployment 3 ;
PROB;62,61,3,1        *Gravity direction Z
FLUI;0,1
LIMI
 1,0,1
 2,885,1,0,1            * Average deployment depth
LLOC
 1,1,62
 2,1,62
BODY
 1,0,.17,0.1875,0.5          *ADL
 2,0,.67,.5,1.167          *ADL + Transponder
 3,0,.22,0.1875,0.5        *Dummy unit
 4,2,1.3,.6,,1.          *Pos 1 PARACHUTE
 7,2,1.3,1,,1.          *Pos 62 PARACHUTE
 5,0,.5,.5,1.167          *Lone Transponder
 6,0,.84,.5,1.667          *Transponder + 2 ADL
MATE
 1,3,.011,0.00166,W7,1600,0,2000,1  *ARRAY LINE
 2,4,0.00517,0.0008,W7,450,0,2000,1 *CONN LINE
BLOC
 4,1                  *PARACHUTE
 2,3                  *1ST TRANSPONDER+ADL
 3,4,6                *DUMMY UNITS
 1,7                  *ADL
 3,8,10               *DUMMY UNITS
 1,11                 *ADL
 3,12,14              *DUMMY UNITS
 1,15                 *ADL
 3,16,18              *DUMMY UNITS
 2,19                 *2ND TRANSPONDER+ADL
 3,27                 *C/L ADL 1
 3,36                 *C/L ADL 2
 2,44                 *3RD TRANSPONDER + ADL
 3,45,47              *DUMMY UNITS
 1,48                 *ADL
 3,49,51              *DUMMY UNITS
 1,52                 *ADL
 3,53,55              *DUMMY UNITS
 1,56                 *ADL
 3,57,59              *DUMMY UNITS
 2,60                 *4TH TRANSPONDER+  ADL
 7,62                 *PARACHUTE
DRAG
 1,2,.90,.85           *HYDROPHONES
 2,2,37.87          * Cross PARACHUTE CdN = CdA,
 3,2,2.4,.02            *ARRAY LINE (Strum Cd = 2.4)
 4,2,3.3,.02           *CONN LINE (Strum Cd = 3.3)
NODE
 1,1,0,0,0
 2,1,0,0,0,2,2,2
 62,1,0,0,0,2,2,2
NGEN
 59,2,62                * STRAIGHT LINE GEN
TFUN
```

```
1,1,0,0,60,1,1        *60 sec ramp from 0 to 1 then const
2,1,0,0,10,100,1      *10 sec ramp for 100 N tension
3,6,0,615              *Ship's track from GPS during payout - NODMOV.TAB
4,3,0,0,.25,
 60,10.98,
 120,11.01,
 180,19.32,
 240,22.31,
 300,23.53,
 360,24.82,
 420,26.53,
 480,28.03,0
FLOW
 1,2,0,.67,.38,0,
 69,.60,.37,0,
 148,.438,.253,0,
 226,.332,.114,0,
 305,.243,.015,0,
 384,.153,-.025,0,
 515,0,-.004,0,
 620,-.09,.02,0,
 751,-.103,.021,0,
 885,0,0,0
PAYOUT
 1,2,1,150,60,10,1,1  *150' mitosis length
ELEM
 1,1,2,,1
 18,18,19,,1
 19,19,20,,2
 43,43,44,,2
 44,44,45,,1
 61,61,62,,1
TABLE
 1,W11,1,27            *Nodal positions and element tensions
* 2,64,80,,64,79,W11,1
*DEAD
DYN
 SOLU,,,,.0125
* FIX,3,11,12,13              *Fixed z motion at zodiac
 MOVE,-1,1,3,1 *, 1,3,1,1,3,1  *Motion of payout node read from a file
 CURR,1,1
 PAYO,1,4,1                    * Tabular TFUN from GPS to payout full array
 TIME,,001,510
 OUTP,,15,W15,1,15,1
DYN
 SOLU,,,,.001
* FREE,11,12,13,621,622,623
 FREE,621,622,623
 CURR,1,1
 TIME,,3900
 OUTP,,30,W15,-1,30,1
END
```

Deployment 3 NODMOV.TAB File

Time	X (ft)	Y (ft)	Z (ft)
.000000E+00	.000000E+00	.000000E+00	.000000E+00
.100000E+01	-.118100E+00	.173500E+00	.000000E+00
.200000E+01	-.354200E+00	.142000E+01	.000000E+00
.300000E+01	-.708300E+00	.284100E+01	.000000E+00
.400000E+01	-.118100E+01	.473500E+01	.000000E+00
.500000E+01	-.177100E+01	.710300E+01	.000000E+00
.600000E+01	-.247900E+01	.994400E+01	.000000E+00
.700000E+01	-.330600E+01	.132600E+02	.000000E+00
.800000E+01	-.425000E+01	.170500E+02	.000000E+00
.900000E+01	-.531300E+01	.213100E+02	.000000E+00
.100000E+02	-.649300E+01	.260400E+02	.000000E+00
.110000E+02	-.779200E+01	.312500E+02	.000000E+00
.120000E+02	-.920800E+01	.369300E+02	.000000E+00
.130000E+02	-.107400E+02	.430900E+02	.000000E+00
.140000E+02	-.124000E+02	.497200E+02	.000000E+00
.150000E+02	-.141700E+02	.568200E+02	.000000E+00
.160000E+02	-.160600E+02	.644000E+02	.000000E+00
.170000E+02	-.180600E+02	.724500E+02	.000000E+00
.180000E+02	-.201900E+02	.809700E+02	.000000E+00
.190000E+02	-.224300E+02	.899600E+02	.000000E+00
.200000E+02	-.247900E+02	.994400E+02	.000000E+00
.210000E+02	-.272700E+02	.109400E+03	.000000E+00
.220000E+02	-.298700E+02	.119800E+03	.000000E+00
.230000E+02	-.325800E+02	.130700E+03	.000000E+00
.240000E+02	-.354200E+02	.142000E+03	.000000E+00
.250000E+02	-.383700E+02	.153900E+03	.000000E+00
.260000E+02	-.414400E+02	.166200E+03	.000000E+00
.270000E+02	-.446200E+02	.179000E+03	.000000E+00
.280000E+02	-.479300E+02	.192200E+03	.000000E+00
.290000E+02	-.513600E+02	.206000E+03	.000000E+00
.300000E+02	-.549000E+02	.220200E+03	.000000E+00
.600000E+02	-.159200E+03	.638600E+03	.000000E+00
.120000E+03	.699850E+03	.111480E+04	.000000E+00
.180000E+03	.184695E+04	.162560E+04	.000000E+00
.240000E+03	.274730E+04	.255790E+04	.000000E+00
.300000E+03	.360000E+04	.357510E+04	.000000E+00
.360000E+03	.444120E+04	.461290E+04	.000000E+00
.420000E+03	.532480E+04	.562930E+04	.000000E+00
.480000E+03	.576990E+04	.614140E+04	.000000E+00
.495000E+03	.585890E+04	.624340E+04	.000000E+00
.510000E+03	.594790E+04	.634540E+04	.000000E+00

APPENDIX B- SEADYN Post-Processing Files

PPROC.FOR - FORTRAN program that converts the nodal positions from SEADYN
PLOT.DAT file into file readable by MATLAB.

```
PROGRAM PPROC
*
    IMPLICIT INTEGER*4(I-N)
    CHARACTER*20 DATAFILE,OUTFILE
    CHARACTER*15 AC(6)
    CHARACTER*10 RNAME,HED(8),IDATE,ITIME
    CHARACTER*24 VERSION
    REAL*8 PARM
    REAL*8 ELT(6)
    DIMENSION IELCD(6)
    REAL*8 X(500),Y(500),Z(500),TIME(500)
*
    PRINT*,"Enter the run name : "
    READ(*,5)RNAME
    DATAFILE=RNAME // '.DAT'
    OUTFILE=RNAME // '.SST'
    OPEN(1,FILE=DATAFILE,STATUS='OLD',FORM='FORMATTED',
    1ACCESS='SEQUENTIAL')
    OPEN(2,FILE=OUTFILE)
    READ(1,10)ITYPE,INFO,NW,PARM,(AC(I),I=1,NW)
    READ(1,20)HED,IDATE,ITIME,VERSION
*
    DO WHILE (.NOT.EOF(1))
        READ(1,10)ITYPE,INFO,NW,TIME(I),(AC(K),K=1,NW)
        ITYPE=ITYPE+90000
        IF (ITYPE.EQ.-1) THEN
         DO 200 J=1,INFO
           READ(1,30)NODE,IDUM1,IDUM2,X(I),Y(I),Z(I)
200      WRITE(2,40)NODE,X(I),Y(I),Z(I)
         ELSE IF (ITYPE.EQ.-2) THEN
           DO 300 J=1,INFO
300        READ(1,35)IELT,(IELCD(I),ELT(I),I=1,NW)
         END IF
      END DO
*
    5 FORMAT(A10)
    8 FORMAT(F8.2)
    10 FORMAT(I6,I5,I4,E15.6,6(A15))
    20 FORMAT(8A10/2A10/A24)
    30 FORMAT(3I5,3E15.6)
    35 FORMAT(I5,6(I3,E12.4))
    40 FORMAT(I5,3F10.2)
    60 FORMAT('        ',13I8)
    70 FORMAT(F8.2,13F8.2)
    80 FORMAT(' ')
600 CLOSE(1)
      CLOSE(2)
      END
```

PPROC2.M - MATLAB script file that converts raw data from SEADYN (processed by PPROC.FOR) into several different data sets that can be plotted using MATLAB or other software. Data sets include: Three dimensional snapshots of deployment only and total descent (automatically plotted), average and total spacings, selected depth histories (saved as ascii file dhist.dat), selected times to bottom (tbot.dat), and deployment track and bottom locations (otb.dat).

```
clear s1
clear s2
load sshot.dat
dd=input('2-D plot (2) or 3-D plot (3) :  ');
filename=input('Enter the run name : ','s');
% n=input('Enter the number of nodes :');
n=62;
sa1=0;
sa2=0;
itot=size(sshot);
k=0;
for j=1:itot(1)/n
 for i=1:n
  x(i,j)=sshot(i+n*k,2);
  y(i,j)=sshot(i+n*k,3);
  z(i,j)=sshot(i+n*k,4);
 end
 k=k+1;
end
m=1;
z=-1*z;
x=1*x;
for j=35:2:k
 for i=1:n
  xd(i,m)=x(i,j);
  zd(i,m)=z(i,j);
  yd(i,m)=y(i,j);
 end
 m=m+1;
end

for i=1:16
 s1(i)=sqrt((x(i+3,k)-x(i+2,k))^2+(y(i+3,k)-y(i+2,k))^2);
 s2(i)=sqrt((x(i+44,k)-x(i+43,k))^2+(y(i+44,k)-y(i+43,k))^2);
 sa1=sa1+s1(i);
 sa2=sa2+s2(i);
end
s1=s1'
sa1
s2=s2'
sa2
avg1=sa1/16
avg2=sa2/16
ti=[filename ': AVG1 = ' num2str(avg1) ' AVG2 = ' num2str(avg2)];
if dd==3
 plot3(xd,yd,zd);
```

```
 grid on;
 zlabel('Depth (ft)');
 xlabel('x Distance (ft)');
 ylabel('y Distance (ft)');
else
 plot(xd,zd);
 ylabel('Depth (ft)');
 xlabel('x Distance (ft)');
end
%title(ti);
%text(500,-50,'30 sec intervals')
figure
if dd==3
 plot3(x(:,1:35),y(:,1:35),z(:,1:35));
 grid on;
 zlabel('Depth (ft)');
 xlabel('x Distance (ft)');
 ylabel('y Distance (ft)');
else
 plot(x(:,1:35),z(:,1:35));
 ylabel('Depth (ft)');
 xlabel('x Distance (ft)');
end
ti2=[filename ' Deployment '];
title(ti2);
text(6000,-300,'15 sec intervals')

itot=size(z,2);
for j=1:12
n=input('Enter node for ttb:  ');
for i=1:itot
 if z(n,i)==-885
  tbot(j)=525/60+((i-35)*30/60)
  break
end
dhist(:,j)=z(n,:)';
end
otb(:,1)=x(:,35);
otb(:,2)=y(:,35);
otb(:,3)=z(:,35);
otb(:,4)=x(:,146);
otb(:,5)=y(:,146);
otb(:,6)=z(:,146);
save dhist.dat dhist -ascii
save tbot.dat tbot -ascii
save otb.dat otb -ascii
end
```

APPENDIX C - Photographs from High Speed Deployment Experiment

Figure C1 - This picture shows the array bobbins in the process of being attached to the frame that will hold them during deployment. The frame is in a horizontal position for the ease of preparation. Each bobbin has a length at its end without cable wraps. This end sits in a PVC cap that is bolted to the frame. Set screws in the caps hold the bobbins in place. Further preparation of the array bobbins includes attaching the ADL and dummy units and connecting the array line ends from one bobbin to the next.
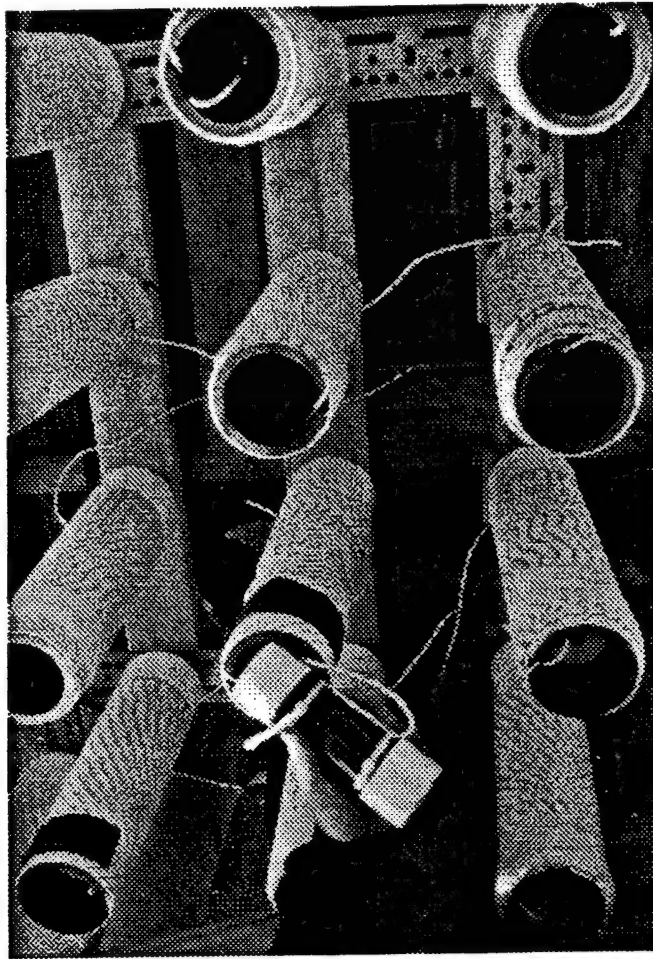
Figure C2 - An ADL unit is being attached to an array line in this picture. The attachment is made with two heavy duty tie wraps. After attachment the unit is lowered into the bobbin and attached to the bobbin inner side by a strip of velcro. A unit already installed can be seen in the bobbin pictured center right.
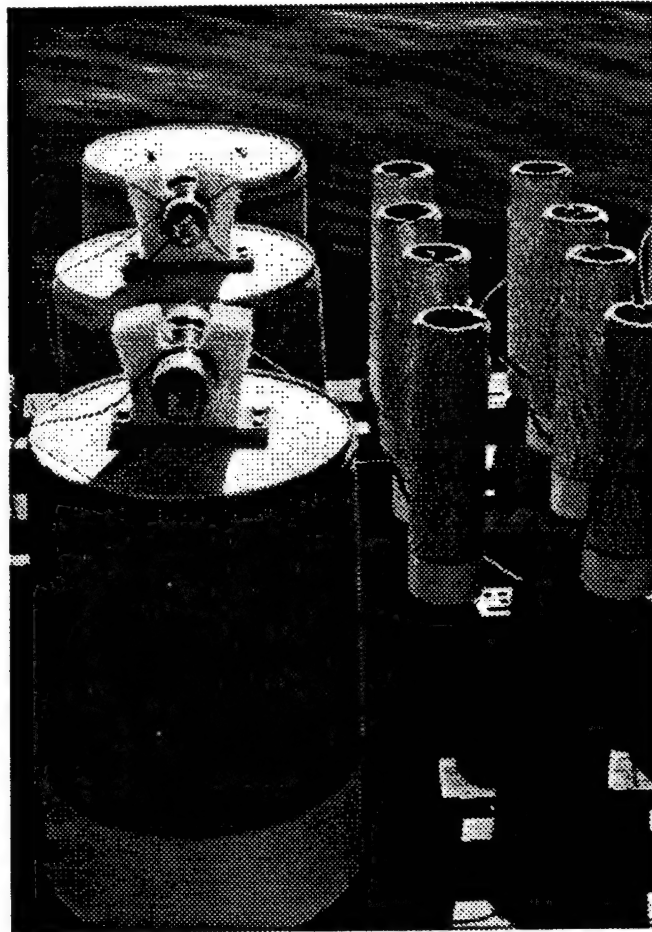
Figure C3- The three large cylinders are the inter array bobbins. 1200 feet of the small diameter inter array cable was wrapped in two layers around each one. ADL units rest in foam mounts on the outer surface of the lower two (in the picture) bobbins. Eight smaller array bobbins can be seen on the right hand side of the photograph. Each bobbin was wrapped with 150 feet of array cable an ADL unit or dummy unit was attached to the inner surface of each bobbin (not seen in the picture). The bobbins were attached to a frame which is shown in the horizontal (pre-deployment) orientation. The inter array bobbins were between two sets of 16 array bobbins.
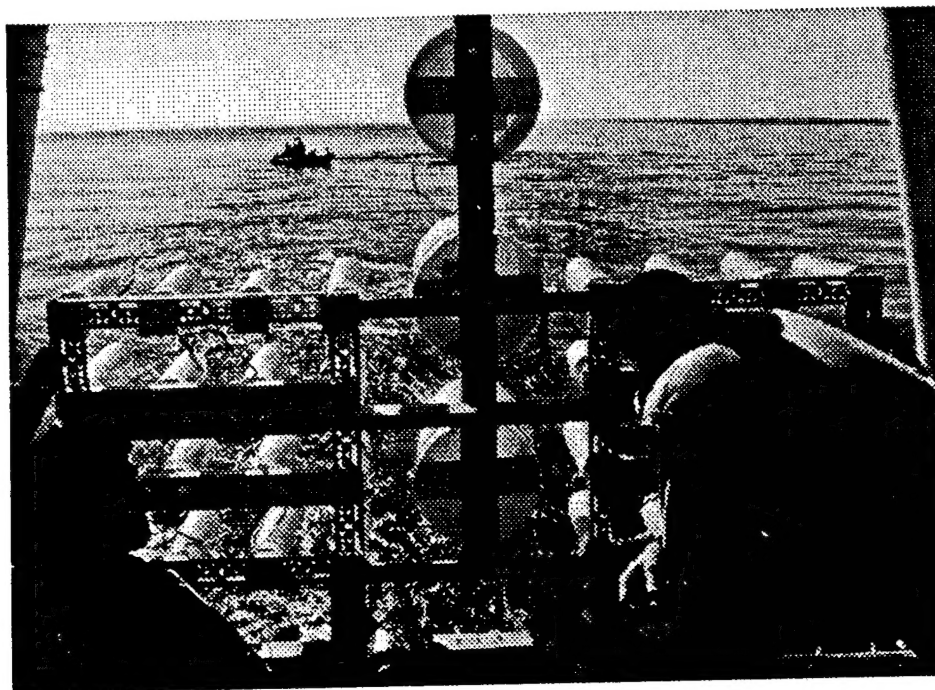
Figure C4 - In this photograph, the bobbin frame has been rotated 90 degrees to its deployment position. The zodiac can be seen to the left of the top inter array bobbin. The zodiac has set the moor for the recovery line and is holding the parachute. The Quest has begun to accelerate away from the zodiac as the cable and instruments are being pulled into the water.
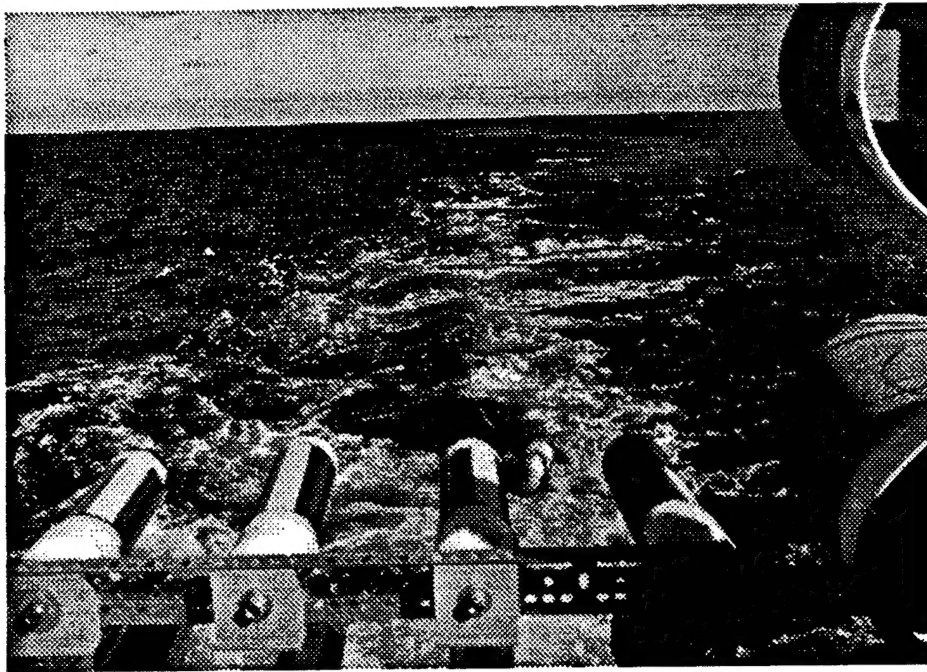
Figure C5 - At this point in the deployment three quarters of the first sub array bobbins have been unwrapped. The far right array bobbin has just been unwrapped and its ADL unit is being extracted. The ADL can be seen between the far right array bobbin and the bobbin next to it. Some of the cable connected to the ADL pulling it into the water can also be seen. The zodiac is now so far away from the moving vessel that it can barely be made out (right hand portion near the horizon).
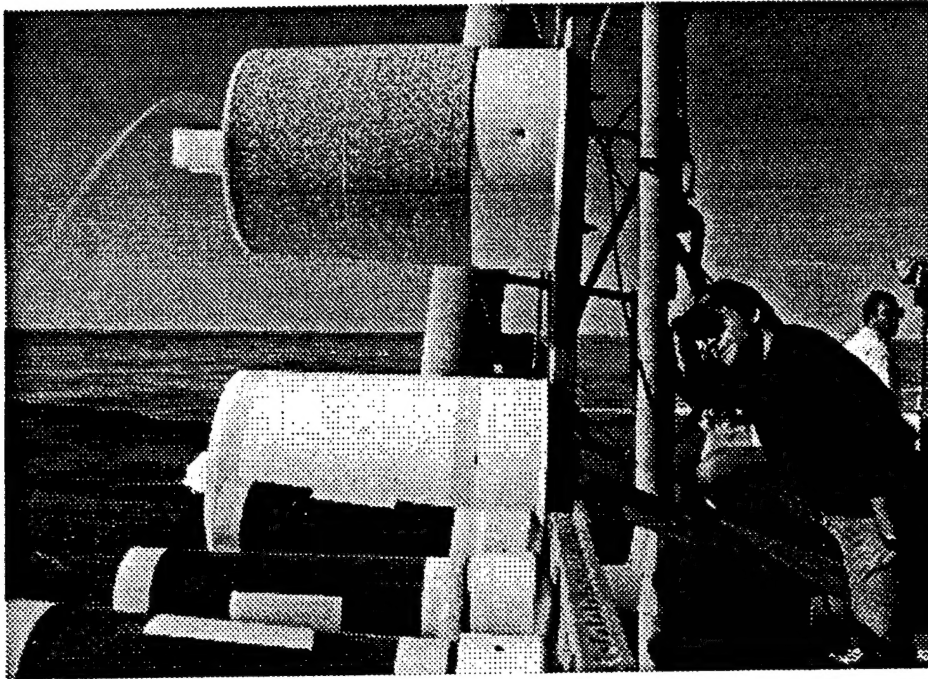
Figure C6 - At this point the deployment has progressed to the inter array cable. Sub array 1 is in the water, two of the three inter array bobbins have been unwrapped, and both inter array ADL units are in the water. The author watches intently as the last inter array bobbin is paid out.

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